Final Technical Report
Earthquake Hazards Program

The Washoe Shear Zone Transtensional Hypothesis, A Reconnaissance Study

Earthquake Hazard of the Washoe Shear Zone, Reno, Nevada

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ABSTRACT

This study develops the hypothesis of the Washoe shear zone, a zone of northwest-striking faults that crosses western Nevada from Verdi (western Reno) to Steamboat Hills, a distance of 28 km. A possible southern extension would increase this distance to 48 km and bring the shear zone east of Carson City. The shear zone has transtensional movement. The translational component is right-lateral strike-slip and the shear zone is part of the Walker Lane belt. The structure is distributed and is made up of multiple faults within a 2 to 3 km wide zone. The northern half of the Washoe shear zone has been divided into three sections which were examined in this study, the Mt. Rose Pediment section, the Northern Carson Range section, and the Mogul-Verdi section. The potential southern extension was not examined in detail for this study, except to take a first cut at the location of possible Quaternary faulting.

The Mt. Rose Pediment section extends from Steamboat Hills, where there is a Quaternary volcano and geothermal activity, to the Carson Range front, where the shear zone truncates the range-bounding fault, the Mt. Rose fault zone. There are two main faults in this section, the Mt. Rose Pediment fault zone and the Arrowcreek fault. The Mt. Rose Pediment fault zone has well-developed, continuous tectonic geomorphology, including compound alluvial fault scarps. The Arrowcreek fault is much subtler in expression, commonly a vegetation lineament, albeit at times a very striking one. Both faults have right-lateral components and movement in the late Quaternary.

In the Northern Carson Range section, the shear zone crosses the range front and is in mountainous terrain. It is challenging to define the late Quaternary faults in this section because of the lack of Quaternary cover and the higher erosion rates in the mountains. Faults in this section appear to be reactivating a network of Miocene faults. The eastern part was called the Ballardini Ranch reach and the main fault within it is named Angela's fault zone. A late Quaternary terrace along the south branch of Evans Creek appears to be disrupted by Angela's fault zone, indicating activity younger than this terrace. The western part of this section is the Caughlin Ranch reach. There are three primary faults in this section, the Caughlin Ranch fault, the Crest fault, and an inferred fault zone to the southwest within the range. A hand trench was dug across the base of a 10-m-high fault scarp along the Caughlin Ranch fault confirming a fault origin for the feature and late Quaternary activity; a reverse fault was exposed which is likely due to a complexity in the fault zone, but a landslide origin needs to be ruled out as the range front may be collapsing between the Caughlin Ranch fault and Crest fault.

The northernmost section is the Mogul-Verdi section, where the 2008 Mogul earthquake occurred. One of the most prominent features in this section is a 2.5-km-long northwest-trending horst ridge, with northwest-striking faults along the sides, the Somersett Ridge fault and the River Bend fault.

The evidence for a right-lateral strike-slip component of the Washoe shear zone includes: 1) occurrence of the 2008 Mogul earthquake (M4.9), a right-lateral earthquake on a northwest-striking fault, 2) northwest-striking faults in a stress regime with a west-northwest least principal horizontal stress direction, 3) left-stepping en echelon steps in faults, 4) flower structures with little vertical offset exposed in trench excavations, 5) local strike-slip focal mechanisms that indicate right-lateral slip on northwest striking planes, 6) right-lateral deflections in several stream channels, 7) strike-slip tectonic geomorphology, 8) northwest-striking fractures producing geothermal fluids, 9) relatively

linear structures indicating steep dips, 10) kinematic consistency with other local faults, 11) alignment of tectonic features, such as volcanoes and basement uplifts.

Earthquake magnitude estimates for individual faults within the zone range from **M**5.6 to **M**6.3. If the north half of the shear zone failed, the potential magnitude is estimated is **M**6.7. If the entire known extent of the shear zone failed, the estimate is **M**7.0. The fault slip rate of the Washoe shear zone is poorly constrained, but estimates of 0.1 to 1 m/ky for the Mt. Rose Pediment section are reasonable.

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ACKNOWLEDGEMENTS

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INTRODUCTION

The 2008 Mogul, Nevada earthquake (**M**4.9) was a northwest-striking right-lateral strike-slip event (Smith and others, 2008; Ruhl et al. 2014) that occurred on a blind fault. The earthquake caused over two million dollars of damage in western Reno. This earthquake presented several important implications for the Reno area, including the occurrence of a damaging strike-slip earthquake in an area where few lateral slip faults had been mapped. The Reno area is part of the Walker Lane belt, a major strike-slip zone, which experiences deformation and earthquakes (Wesnousky, 2005; Kreemer et al., 2012). Given the location of Reno within the Walker Lane, it is perplexing that more strike-slip faults have not been mapped in the area. Several strike-slip faults have been recognized (Ramelli et al., 2011; Brailo, 2016) but they are not in an organized zone. Following the Mogul earthquake, Bell et al. (2012) examined InSAR data and identified a northwest-trending geodetic lineament. The Mogul earthquake occurred along this gradient, which was found to extend a significant distance southeast from the event. Based on the geology, the Mogul earthquake, and the geodetic lineament, Bell et al. (2012) interpreted that there was a westward migration of dextral shear into an extensional Reno basin.).Ruhl et al. (2016) examined seismicity in the Reno-Tahoe area and identified a northwest-trending transtensional seismic source zone they called the "Mogul-Border Town seismic source zone. Scientists are finding reasons to suspect a strike-slip component along faults in this region.

This study set out to examine a hypothesis that a series of northwest-striking faults adjacent to southwestern Reno make up a right-lateral strike-slip zone of late Quaternary deformation. The result was the recognition of a 28- to 48-km-long zone of faults in western and southern Reno, named the Washoe shear zone (fig. 1). A major earthquake along the Washoe shear zone would have substantial consequences to the Reno-Carson City urban corridor.

The zone is difficult to study and much of it is in mountainous terrain. Features examined along the zone indicate that any single fault within the zone has a moderate or low fault slip rate. Such faults are hard to recognize and characterize, especially in the mountain. In this setting erosion rates can exceed fault slip rates. Additionally, throughout the Washoe shear zone, activity is distributed across multiple faults.

During this study, it became evident that the zone likely extended beyond initial mapping, possibly extending 20 km southeast into the Virginia Range. For this reason, a large range in potential length was stated. Fault traces that may belong to the southern half of the Washoe shear zone were rapidly identified, but ultimately were not studied in detail due to overextended resources. At this time, the ends of the zone are debatable, and may in fact extend farther than shown in this report.

The northern half of the Washoe shear zone is divided into and described as three main sections: the Mt. Rose Pediment section, the Northern Carson Range section, and the Mogul-Verdi section (fig. 2). These sections are further subdivided where appropriate. Faults compiled and mapped by Ramelli et al. (2011) were initially used in this study. Faults mapped by Tabor and Ellen (1975), Henry and Perkins (2001), Hudson et al. (2009), Trexler et al. (2012) and Cashman et al. (2012) were added to the Ramelli dataset as well as faults mapped or inferred during this study. This is a reconnaissance level study and detailed studies are needed for most fault traces, with the exception of some fault traces in the Mt. Rose pediment section that have been evaluated for housing developments. Most of the new potential faults outlined in this study are inferred based on geomorphology. Geology, aerial photography, Google Earth, and limited LiDAR data were examined to develop the locations of these possible faults.

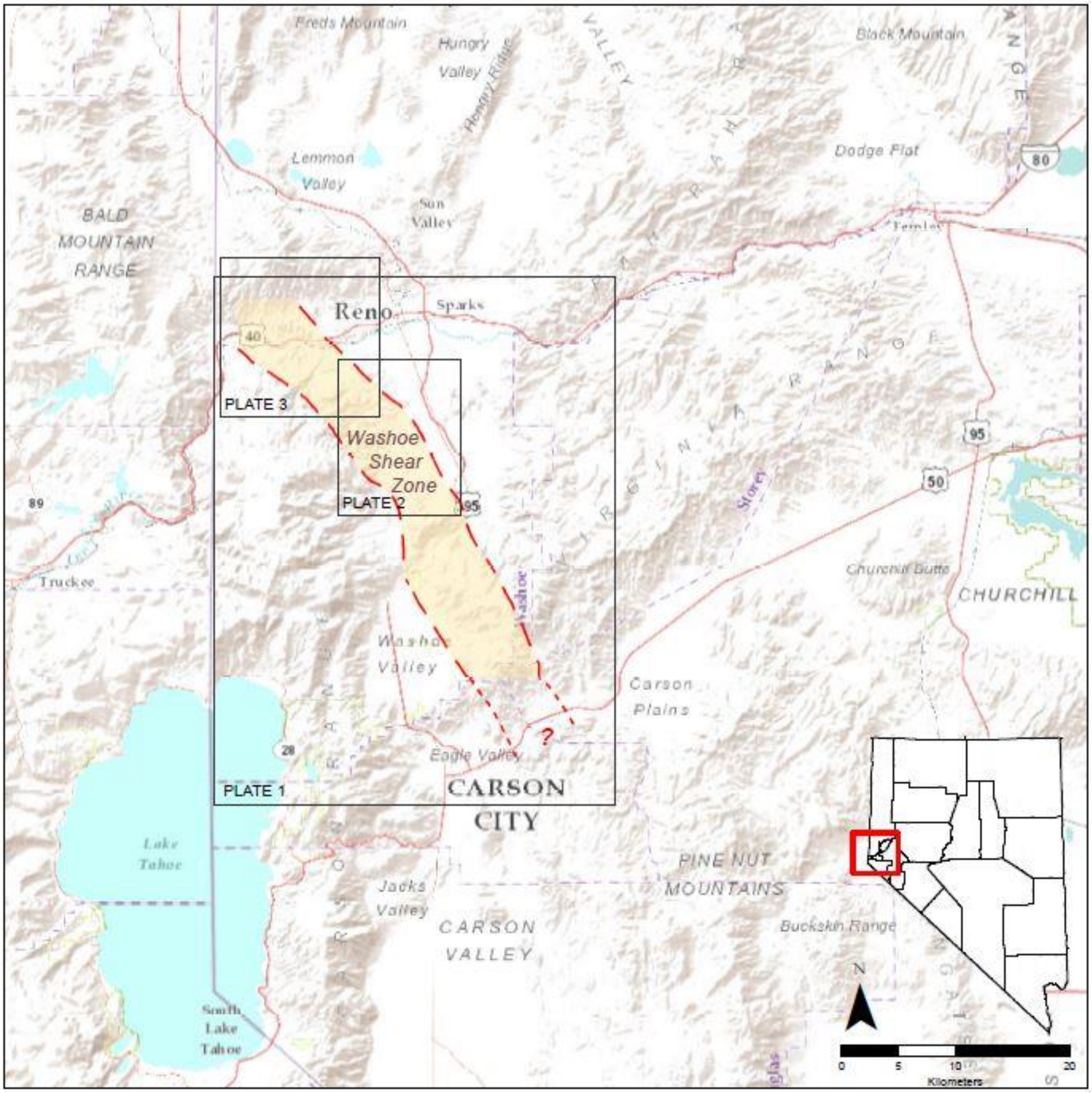


Figure 1. Location map showing the study area, the boundaries of the Washoe shear zone, and the outlines of the plates included in this study.

Figure 2. General outline of the Washoe shear zone and the sections and reaches that are discussed in the text.

This report covers the northern half of the Washoe shear zone from north to south. The southern end of this half is at Steamboat Hills, an area of uplift with a Quaternary volcanic center. North of these hills, faults in the zone have formed in a large Quaternary pediment complex known as the Mt. Rose pediment. The zone continues to the north, crossing the northern flank of the Carson Range and truncating the Mt. Rose fault zone - the eastern bounding normal fault of that range. The shear zone continues northwest into the Mogul-Verdi area. Mapping was stopped at the California-Nevada state line (fig. 1).

2008 MOGUL, NEVADA EARTHQUAKE

The most definitive information to date that the Washoe shear zone is a late Quaternary fault zone with a right-lateral strike-slip component was the 2008 earthquake activity near Mogul, Nevada, about 7 to 8 km west of Reno (Smith et al., 2008; Anderson et al., 2009; Ruhl, 2016; Ruhl et al., 2016). Most of the foreshocks and aftershocks appeared to have strike-slip focal mechanisms (Smith and others, 2008; Ruhl et al., 2016), multiple fault traces appeared to have seismic activity during the sequence (Ruhl et al., 2016), and the mainshock of M_w 4.9 was a right-lateral strike-slip event. This event was unusually shallow (~3.1 km below the surface; Smith et al., 2008) and produced exceptionally high ground motions for its size (Anderson et al., 2009). Thus, even though faults within the Washoe shear zone are discontinuous and distributed, it may have characteristics that could cause strong ground motion. One of the most interesting observations made from 2008 activity relative to the Washoe shear zone was from InSAR data related to the Mogul earthquake (Bell et al., 2012) which showed that deformation occurred along the two northern sections of the Washoe shear zone (this InSAR boundary is displayed by Ramelli et al.. 2011 and shown in plate 1).

WASHOE SHEAR ZONE

As previously mentioned, three sections of the Washoe shear zone are discussed in detail. The northern two sections trend more westerly (N50°W) than the Mt. Rose Pediment section (N30°W), The middle section, the Northern Carson Range section, was further subdivided into two reaches, the Caughlin Ranch reach and the Ballardini Ranch reach. Also noted is the southern shear zone, which was treated as a single entity without further subdivision. The southern shear zone has an overall trend of N35°W. Table 1 gives the dimensions of the sections and reaches of the Washoe shear zone.

Table 1. Dimensions of the sections and reaches of the Washoe shear zone.

Section	Reach	Length (km)	Width (km)
Mogul-Verdi		7.5	3
N. Carson Range	Caughlin Ranch	6	2.5
N. Carson Range	Ballardini Ranch	6	2.5
Mt. Rose Pediment		8,5	2
Southern Shear zone		20	5.5

Mt. Rose Pediment Section

The Mt. Rose pediment is a large pediment that is adjacent to the eastern side of the northern Carson Range. The pediment is made up of Quaternary alluvium and glacial outwash deposits overlying an erosional unconformity on tilted Tertiary sediments of the Hunter Creek Sandstone. There are parts of this landform where the overlying alluvium is likely thicker, especially closer to locations where major glaciated drainages exited the range. The pediment surface is broken up by a myriad of faults that have formed fault scarps and surficial lineaments (Bonham and Rogers, 1983; plate 1 and 2). The Washoe shear zone crosses the pediment in its northeastern part with a two-kilometer-wide zone of northwest and northerly striking faults (fig. 3). The deposits fault scarps were formed in are mapped by Ramelli et al. (2011) as older glacial outwash (Qoo) and older fan deposits (Qfo). Two luminescent dates were collected in the Dry Creek area of these Quaternary sediments by Briggs et al. (2015). These dates were 79 ±5 ka and 65 ±4 ka, indicating the surficial alluvium correlates with the latest Sagamonian interglacial or the Tahoe glacial periods. Other parts of the pediment are covered with younger alluvial sediments, which can be observed near Whites Creek immediately north of Steamboat Hills (Ramelli et al., 2011). There are likely older mid-Quaternary parts as well. The faults within the Mt. Rose Pediment section are some of the most continuously expressed and robustly developed Quaternary fault traces along the Washoe shear zone.

Along the Mt. Rose Pediment section of the Washoe shear zone, Quaternary fault scarps and lineaments have several left steps between them (Plate 2; fig. 3). This en echelon stepping nature of the fault scarps and related lineaments has been recognized since Thompson and White (1964) mapped them and included an aerial photograph of them (their Figure 16.). The en echelon character to the fault scarps is a significant clue for the existence of a right-lateral component along the shear zone.

The Washoe shear zone in the Mt. Rose pediment section has two main faults, the Mt. Rose Pediment fault zone and the Arrowcreek fault, along with several adjacent secondary, subparallel traces (Plate 2). The two main faults merge just north of Thomas Creek. The Arrowcreek fault trends towards the Carson Range, whereas the Mt. Rose Pediment fault zone trends more northerly towards the Reno basin.

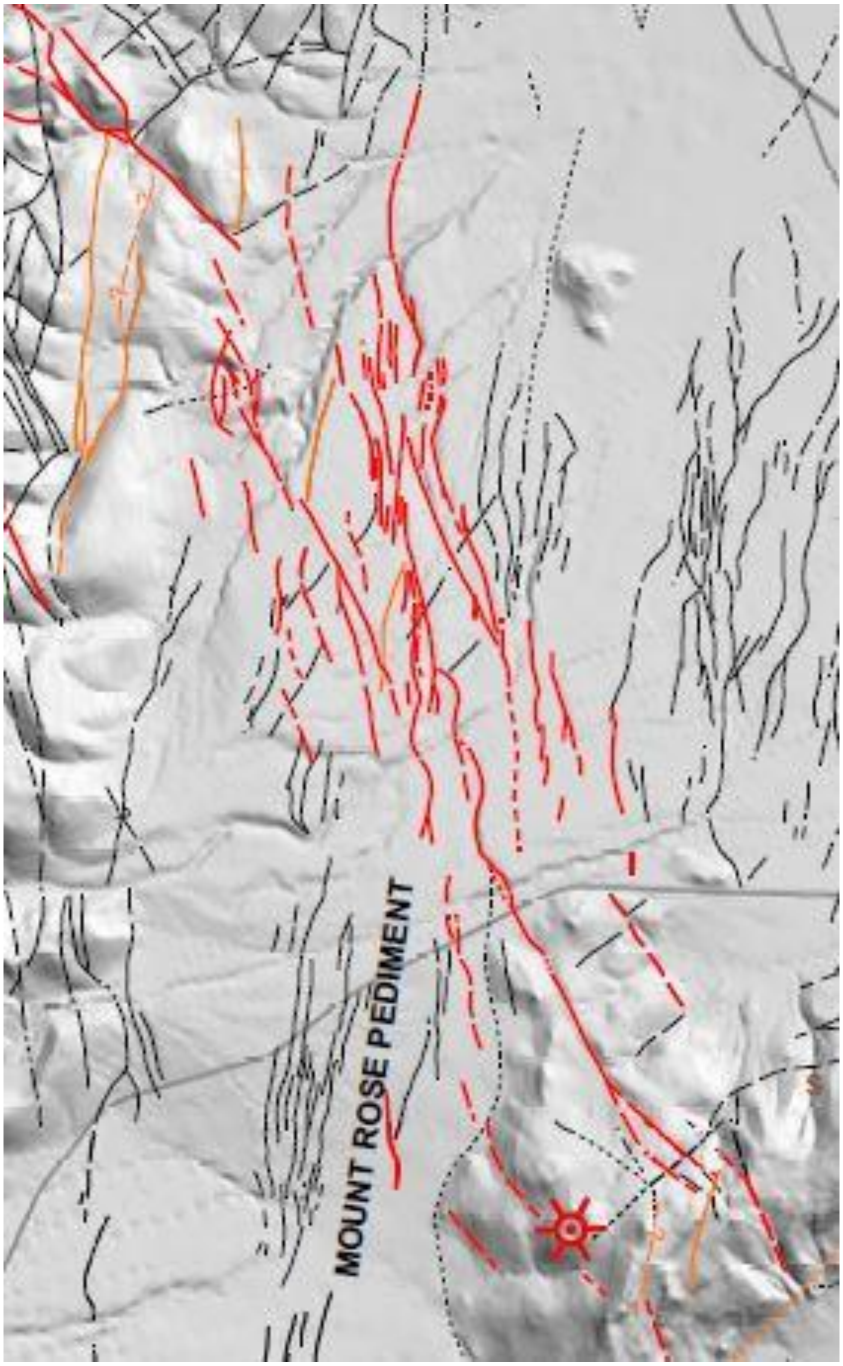


Figure 3. Section of Plate 1 showing the Mt. Rose Pediment section of the Washoe shear zone. North is towards the top of the figure. Steamboat Hills are in the lower right-hand corner and the Carson Range is along the western side of the figure.

Structurally, the Washoe shear zone truncates two late Quaternary normal dip-slip faults along this section and separates two domains of faults in the pediment. The two truncated faults are the Mt. Rose fault zone and the Reno fault zone (also known as the Virginia Lake fault zone or the Virginia Street fault). The two domains are north and south of the shear zone. Faults in the pediment to the south of the shear zone tend to have northerly strikes, subparallel to the range front fault. Faults to the north of the zone tend to have northeasterly strikes.

Much of the Mt. Rose pediment is built over or modified with landscaping and golf courses, and only a little of the original landscape remains. Fortunately, good photography, including 1972 low-sun-angle photography flown by Dr. David “Burt” Slemmons exists and detailed mapping of the faults was conducted in the pediment prior to development. The offsets in the pediment surface made it relatively easy to map the fault zone in detail. Nearly all the faults considered in this section were previously mapped by Bonham and Rogers (1983), Szecsody (1983), and Ramelli et al. (2011).

Mt. Rose Pediment fault zone

The Mt. Rose Pediment fault zone (Plate 2) has been recognized by several scientists (c.f., Thompson and White, 1964; Bonham and Rogers, 1983; Ramelli and others, 2011; Brailo, 2016), but is named here as a fault zone. It is a predominantly back-facing (west-facing) series of fault scarps and uplifted features that cross the northeastern part of the pediment. Parts of this fault zone have been called the “West Steamboat fault” by Ramelli et al. (2011; see their cross sections E-E’ and F-F’). The West Steamboat fault is an insightful recognition and may be a key in understanding connections between the Mt. Rose Pediment fault zone and normal faults to the north, but it does not coincide with some of the most important elements of the Mt. Rose Pediment fault zone as it has been defined here. Thus, the West Steamboat fault is considered an element of the Mt. Rose Pediment fault zone.

The Mt. Rose Pediment fault zone extends from Steamboat Hills, northward to the foothills of the Carson Range, where it changes to a more northerly strike parallel to the range front. The northern part is located a little east of the range front. The southernmost end of the fault zone intersects the Pleasant Valley fault, a northeast-striking normal dip-slip fault on the northwest side of Pleasant Valley. The northern end of the fault zone appears to merge with the Reno fault zone (a northerly striking normal dip-slip fault; Plate 1). The total length of the Mt. Rose Pediment fault zone is 10 km. Six kilometers of the fault is north of the intersection with the Arrowcreek fault. South of this intersection the zone has a N30°W strike whereas to the north, the zone has a strike of about N6°W. The fault zone is as much as 0.75 km wide and individual fault traces within the zone are 0.25 to 4 km long. Individual faults have northwest, north-northwest, and northerly strikes and although the larger offsets are down-to-the-west, some down-to-the-east faults are present as well, sometimes as antithetic graben structures (Bonham and Rogers, 1983). Geomorphic features along the fault zone include single-event and compound fault scarps, back-facing fault scarps, tonal and vegetation lineaments, graben, deflected drainages, and boulder lines. Compound fault scarps have vertical offsets as much as 23 m (Ramelli et al., 2002; Profile Dry Creek 1B).

The southern end of the Mt. Rose Pediment fault zone is proximal to Quaternary volcanic and geothermal activity. One kilometer to the west of the southern end in Steamboat Hills is a Quaternary rhyolitic dome intrusion (Tabor and Ellen, 1975; Ramelli et al., 2011) with a date of 1.2 Ma (Ramelli et al., 2011). To the east of the end of the fault zone is the Steamboat Springs geothermal field. Within 0.5 km of the southernmost inferred trace, and potentially directly intersecting faults of the Washoe shear zone, are two interpreted down-to-the-north normal faults with strikes of N75°W that are producing geothermal water (Walsh et al., 2010). These faults are interpreted from the alignments of producing geothermal wells, a parallel gravity gradient, fracture orientations from one of the producing wells, and corresponding tonal and weak topographic lineaments on the surface (Walsh et al., 2010). These interpreted faults intersect the Pleasant Valley fault at their southern end. Much of the rest of the producing well field is related to the Pleasant Valley fault and parallel northeast striking faults (Walsh et al., 2010). Walsh et al. (2010) note that the maximum horizontal stress measured by borehole breakouts in producing wells in the field would predict closed fractures in the N75°W direction, yet wells along these fractures have similar productivities as other wells on the northeast-striking structures. To account for the fracture flow, Walsh et al. (2010) call upon oblique slip on these northwest fractures causing irregularities in the fault to be popped open during movement, or a local strain transfer onto these faults from the Pleasant Valley fault. Given their location and orientation, these interpreted, geothermally producing fractures would be part of the Washoe shear zone.

The main trace of the Mt. Rose Pediment fault zone goes through the central part of Steamboat Hills (Bonham and Rogers, 1983; Ramelli et al., 2011). Other northwest striking faults in Steamboat Hills, especially the western part and western side of the hills, may also be part of the shear zone. The main geomorphic expression of the faults through the Steamboat Hills is the formation of a linear valley and small interior basin. The fault is along the base of an escarpment on the eastern side of these features.

The fault zone between Whites and Thomas Creeks is made up of west-facing fault scarps that are back-facing to the eastward slope of the pediment (Plate 2). The main fault scarp is a large sinuous compound scarp. Ramelli et al. (2005) measured a 13.4 m down-to-the-west vertical offset along this part of the fault using 2-foot contour topographic maps available from Washoe County (Profile Saddlehorn 1). This scarp dies out before it reaches Thomas Creek and there is a left step to a smaller back-facing scarp that crosses the creek (fig. 4). Thompson and White (1964) noticed that Whites Creek was more entrenched as it crossed the shear zone (this can viewed on Plate 2).

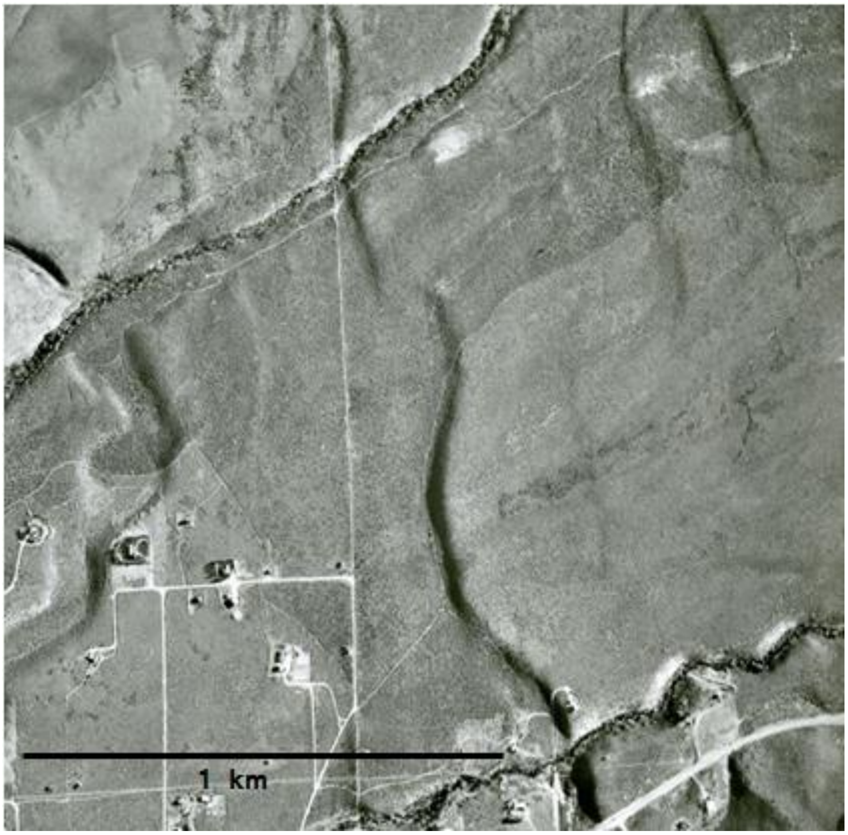


Figure 4. View of the southern part of the Mt. Rose Pediment fault zone between Whites Creek (south or bottom of photo) and Thomas Creek (upper part of photo). Two secondary, subparallel faults can be seen in the upper right of the photograph. View is section of a low-sun-angle photograph taken in 1972 by David “Burt” Slemmons. North is towards the top of the photograph.

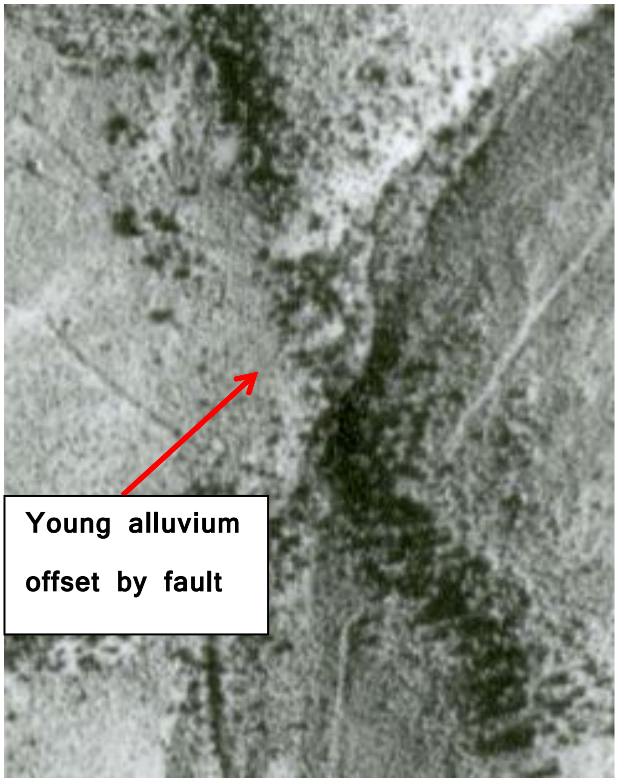
North of Thomas Creek is the intersection between the Mt. Rose Pediment fault zone and the Arrowcreek fault. The two faults are not mapped as directly connecting to each another, rather the Arrowcreek fault approaches the Mt. Rose Pediment fault zone but dies out before it reaches it (Bonham and Rogers, 1983). A fault trace that is difficult to discern on photography is mapped as a southward splay off the Mt. Rose Pediment fault zone and fills the gap between the two intersecting faults. This creates a left-stepping relationship between the two faults. With the exception of small steps, the Mt. Rose Pediment fault zone is continuous through this intersection, but it changes to a more northerly strike by 24°. It is interesting to note that there is background seismicity in the area of this intersection between these two fault zones.

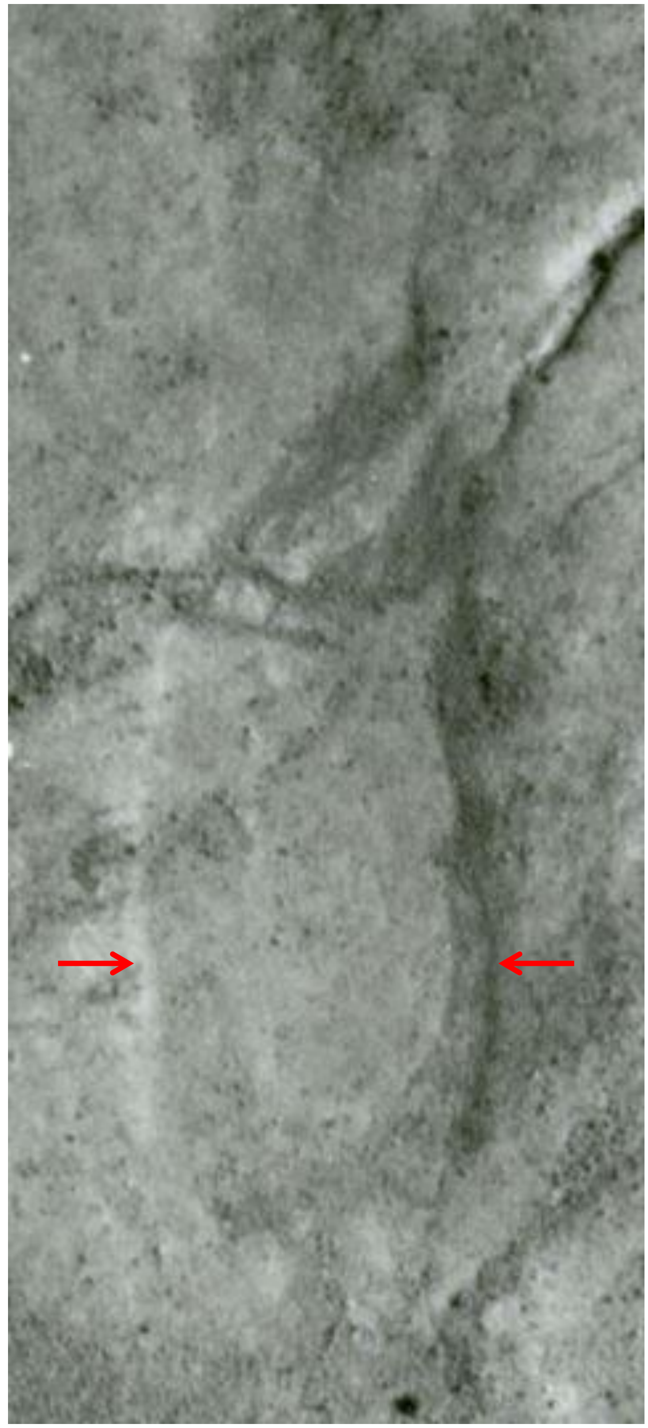
The northern half of the Mt. Rose Pediment fault zone has a complex late Quaternary structural pattern made up of single-event and compound fault scarps, linear ridges, swales, uplifted and tilted blocks, graben, horsts, vegetation and tonal lineaments, and right-deflected stream channels; examples are shown in Figures 5 through 9. These features indicate that recent (probable Holocene) and repeated late Quaternary activity has occurred along the Mt. Rose Pediment fault zone. Also along the northern part of the fault zone, a 3.5 x 1 km area of the pediment along the northeast side of the fault has been uplifted and tilted to the northeast; this shows that the pediment itself is being broken up by this fault zone.

Figure 5. Low-sun-angle photo of fault traces from the Mt. Rose Pediment fault zone. In the central part of this photo are left-stepping secondary fault traces indicated by vegetation lineaments and small fault scarps; these are consistent with a right-lateral strike-slip component along these faults. Also visible are some right-laterally deflected stream channels at the fault crossings and beheaded and dammed drainages. Photograph taken in 1972 by David B. Slemmons.

Figure 6. A fault scarp south of drainage (intersecting the fault from the right) continues north of the drainage as vegetation lineament. Fault is between the red arrows. North is towards the top of the photograph. Photograph taken in 1972 by David B. Slemmons.

Figure 7. Drainage intersecting a fault scarp of the Mt. Rose Pediment fault zone that shows an apparent right deflection at the fault. North is towards the top of the photograph. Photograph taken in 1972 by David B. Slemmons.





Figures 8 and 9. Evidence for a young event along the Mt. Rose Pediment fault zone. In the upper left photograph, young channel fill alluvium has been offset. In the photograph on the right, a subtle (single-event?) graben is seen with highlighted and shadowed faults. For scale, the graben 85 to 100 m across. North is towards the top of the photograph. Photograph taken in 1972 by David B. Slemmons.

Several of the fault traces of the Mt. Rose Pediment fault zone were trenched prior to putting housing developments on the pediment. The trenching was conducted by private consultants; however, these logs are not available for dissemination. In nearly all cases, where a potential fault indicator was observed on the surface, such as a vegetation lineament, a fault was found. The judgement that determined whether the fault trace was set-back from or not was whether the argillic (Bt) soil horizon was faulted. Part of the consultants' success in locating faults was a result of the context they were working with. Lineaments aligned with fault scarps, which was partly due to excellent visibility of faults and their recording with pre-development low-angle-photography. In looking at different aerial photography, vegetation lineaments appear to come and go through time, likely dependent on the annual weather. Development on the pediment has erased many of the small scarps and lineaments (golf courses have been developed over the faults) making the earlier recording of features critical.

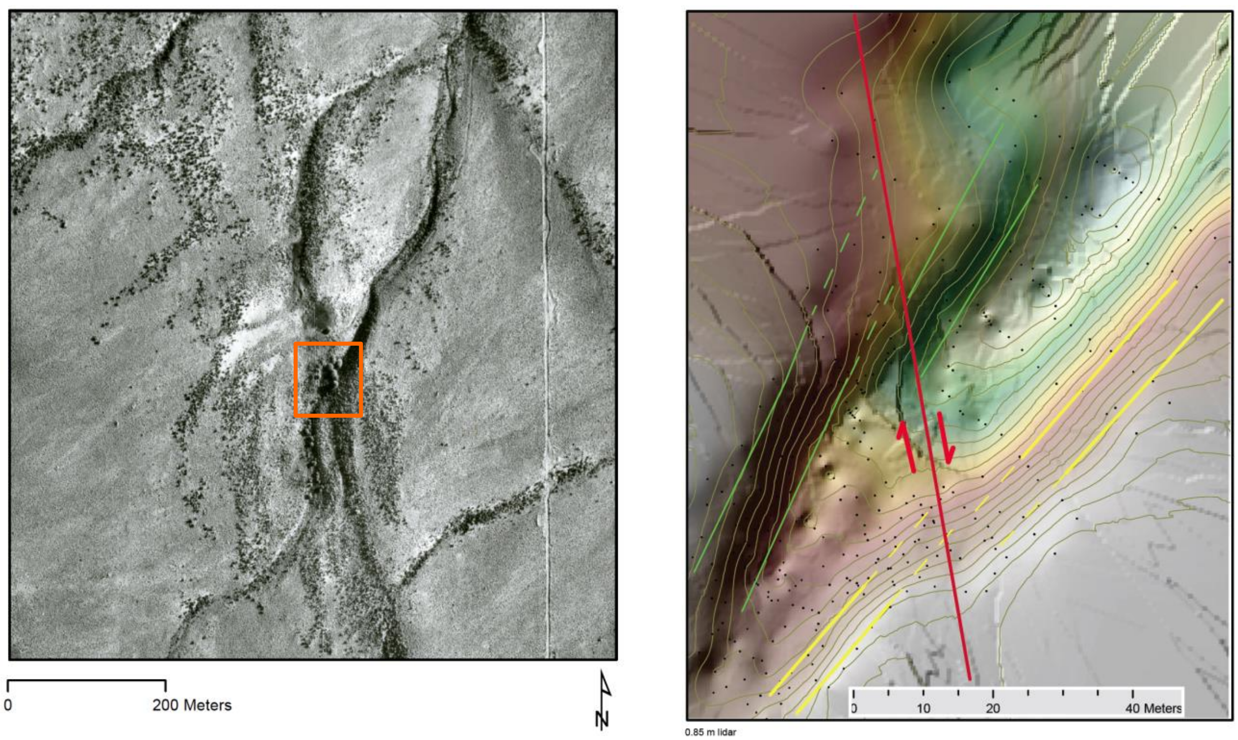
The general stratigraphy was similar for most of the trenches across the Mt. Rose Pediment fault zone and across the Arrowcreek fault. There is a thin, capping, dark-brown sandy "A" horizon (commonly a mollic epipedon), overlying dark-brown or red-brown sandy clay that forms a "Bt" or argillic horizon. Below this is a strongly carbonate cemented gravelly or sandy deposit that constitutes the parent material and a "Bk" or carbonate soil horizon. The age of the fan deposits is still not well known. The recent late Pleistocene dates by Briggs, et al. (2015) were to the north of the trench sites, but may well be from the same surficial deposit. It is also possible that the part of the pediment where the trenches are located is older.

The number of unusual features in these trench logs is remarkable. Many do not look like the common visual of an excavation across a normal fault scarp. The large fault scarps were avoided out of hand because they were obvious, so many of the trenches were across lineaments and small scarps. This may partly explain these unusual features, but a lateral component to the fault movement would be consistent with most of the features. The excavations revealed some steeply dipping reverse faults, and steeply dipping and shallowly dipping normal faults. In many trenches there was limited vertical offset across the main fault and upward-opening fault flower structures were present. Fault gouge was found in a number of cases. Other features include steeply dipping clay-filled cracks and fissures, disruption or truncation of the argillic horizons, and vertically aligned cobbles and imbricate gravels within fault zones.

The fault activity along the Mt. Rose Pediment fault zone was interpreted to be pre- or post- the Bt horizon and further interpreted to be Holocene active if the Bt horizon was deemed faulted. In only a few cases could the Bt horizon be seen as faulted, when it was juxtaposed against a different material. In most cases, a change in thickness across the fault was the evidence of offset or the Bt horizon was otherwise disrupted. A criterion sometimes used in the judgement of fault activity was if the top of the Bt horizon was offset or not. It is possible that in some cases where the top of the horizon did not seem to be offset, it actually was offset and the surface was stripped down by erosion to that horizon erasing the offset. Alternatively, a lateral component to the displacement may not have created visible vertical offsets. The clayey Bt horizon is presumably shrinking and swelling to a degree that in most cases any prior fault fabric within it has been destroyed.

A first overall paleoseismic interpretation would be that most of the larger faults and some of the secondary faults have likely had young, possibly Holocene, movement. Other smaller secondary faults may have moved during some earlier events, but not during the most recent event as the Bt horizon was judged not to be offset. On one of the larger fault scarps trenched, the strongly cemented horizon was not encountered on the downthrown side of the fault and there was a colluvial deposit likely related to fault activity. Future trenching of some of the larger scarps may reveal the late Quaternary history of the Mt. Rose Pediment fault zone. For now, many of the larger faults in the zone are assumed to have had latest Quaternary activity, possibly Holocene activity, and to have had repeated activity during the latest Quaternary. This is in contrast to the mapping by Szecsody (1983), which indicated these faults had mid to early Pleistocene activity.

A right-lateral component along the Mt. Rose Pediment fault zone is indicated by right laterally offset drainages (example shown in Figure 7), left-stepping en echelon faults, and the overall northwest strike in a west-northwest directed horizontal extension stress regime. The largest possible lateral offset measured by the USGS was about 100 m at Dry Creek (Briggs et al., 2015). Other offset measurements were 8 to 16 m (figs. 10a and 10b). If the luminescence ages collected represent maximum ages for these offsets, the right-lateral slip rate is roughly between 0.1 and 1 m/ky along the Mt. Rose Pediment fault zone.



Figures 10a and 10b. Two figures illustrating a potential right-lateral offset of a stream channel. The measurements and figures are from the U.S. Geological Survey and were presented in Briggs et al. (2015). The stream channel has an apparent right lateral offset of 8 to 16 m.

The Mt. Rose Pediment fault zone is interpreted to be related to the Washoe shear zone. The consistent down-to-the-southwest normal component along it may be related the extension in the western Reno basin to the north. This is also implied by the West Steamboat fault of Ramelli et al. (2011).

Arrowcreek fault

The Arrowcreek fault extends from its intersection with the Mt. Rose Pediment fault zone just north of Thomas Creek to the foothills of the northern Carson Range, a distance of about 3 km. The Arrowcreek fault is more subtle in topographic expression, in contrast to the Mt. Rose Pediment fault zone. With exception of its westernmost part, there is very little relief across the fault. Private trenching studies have confirmed that this feature is indeed a late Quaternary fault. The normal component must be limited to account for the lack of topographic relief. The main geomorphic feature is a remarkably sharp vegetation lineament (fig. 11), There are also tonal lineaments, elongate mounds, and along the western part, small fault scarps.

Trenching by private consultants (not yet available for dissemination) confirms that the lineaments associated with the Arrowcreek fault were created by fault movement. Tectonic features that were exposed include clay fault zones, tension cracks, vertical clay filled fissures, variations in thickness of argillic horizons over the fault, and possible upward-opening fault flower structures.

Evidence found in trenches explains the vegetation lineament quite nicely as being a faulted solid calcrete layer that allows roots to penetrate into the moister sediments below. In the case of the secondary fault in Figure 11, the fault does not appear to extend south of the vegetation lineament.

The trenching studies in the southern part of the Arrowcreek fault suggested that the argillic B horizon was not offset. In the northern part of the fault, the argillic horizon was considered faulted by the most recent event in late Pleistocene or Holocene. Thus, the Arrowcreek fault is a late Quaternary fault

Figure 11. Remarkable lineament along the Arrowcreek fault. The relationship to a fault was confirmed by trenching by a private consultant. The lineament is caused by fracturing of a well-cemented calcrete horizon allowing roots to penetrate to the moist deposits below.

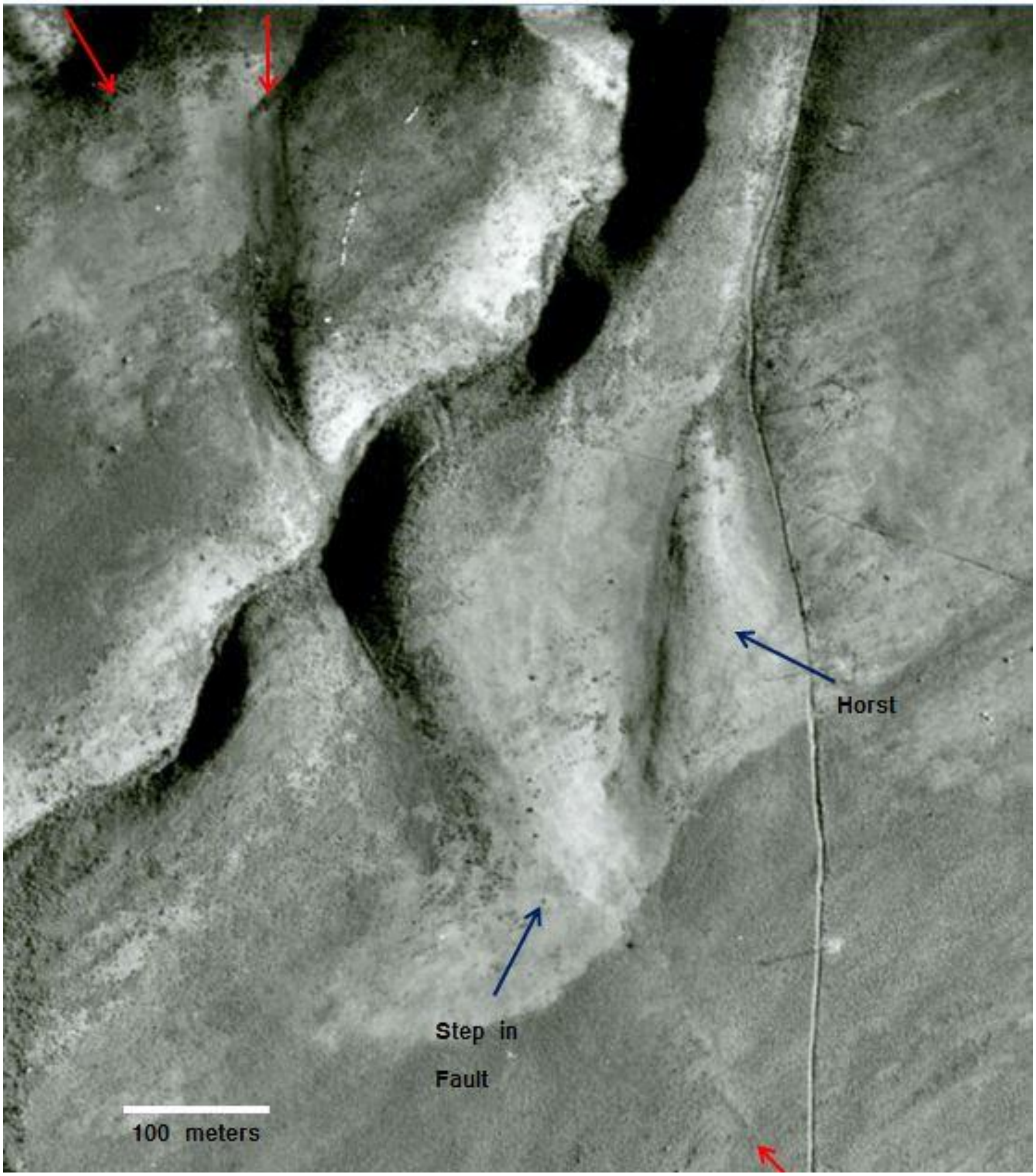


Figure 12. The northwestern part of the Arrowcreek fault (between the red arrows). The fault comes up from the lower right side of the photograph to the location where it steps left and also intersects a northerly striking fault that bounds the west side of a horst. After the left step the fault goes down an eroded fault scarp, crosses a tributary of Dry Creek, and bifurcates into two faults in the upper left part of the photograph. North is towards the top of the photograph. Low-sun-angle photograph taken in 1972 by Dr. Burt Slemmons.

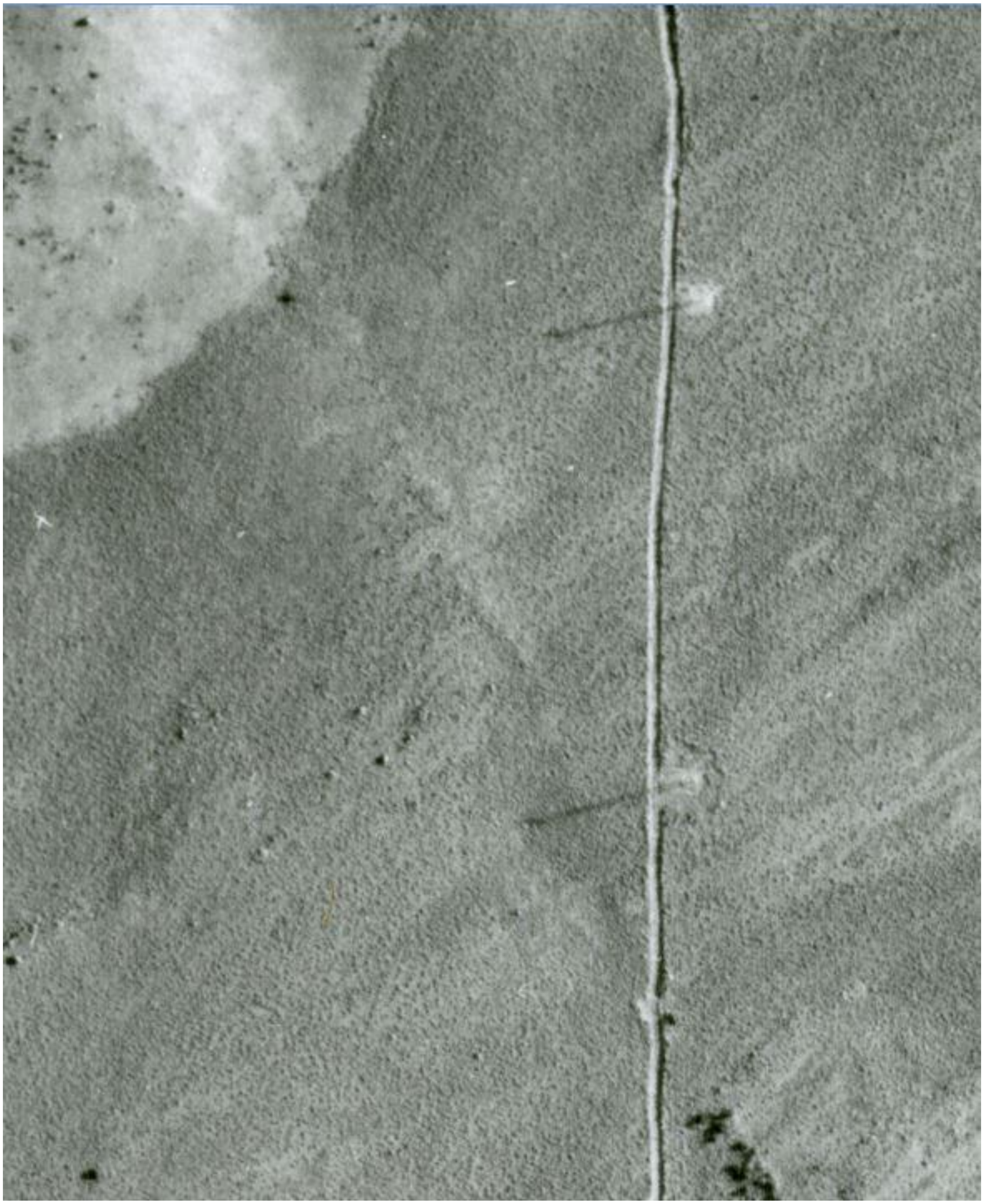


Figure 13. Section of the lower part of Figure 12. Lineament along the Arrowcreek fault with possible push-up mounds along it. The lineament crosses the photograph from the upper left to the lower right. Low-sun-angle photograph taken by Slemmons (1972).

Secondary faults

There are several secondary faults mapped in the Mt. Rose Pediment section of the Washoe shear zone and these generally make up the two-kilometer width of the zone. The secondary faults have northwesterly or northerly strikes, but they have different characteristics on the west side of the shear zone, versus the east side. Secondary faults on the western side of the shear zone are discontinuous, mostly ≤1 km in length, have little relief across them, and are commonly expressed as vegetation lineaments (fig. 3; Plate 2). On the eastern side of the zone, secondary faults are 1 to 4 km long, commonly form alluvial fault scarps, and have more continuity. Fault scarps associated with secondary faults on the east side commonly are small, but one scarp near Thomas Creek profiled by Ramelli et al. (2002) had a vertical offset of 8.4 m (Profile Lower Thomas 2). These secondary faults might break during earthquakes along the shear zone, but only the longest ones might be individual earthquake sources.

Mt. Rose fault zone

The Mt. Rose fault zone bounds the eastern side of the northern Carson Range and forms the southern part of the Reno basin. It is a 34-km-long east-side-down normal dip-slip fault, with a poorly constrained vertical fault slip rate of 1.5 m/ky (dePolo, 2009). Along its northernmost part the fault zone follows the tilted contact between the Hunter Creek Sandstone and the volcanic rocks of the Kate Peak Formation. Thus, facets above the range-bounding fault trace are also dip slopes. The amount of these slopes that is tectonic versus the amount of these slopes that is due to differential erosion is an open question.

The Mt. Rose fault zone has a horsetail splay in its northern part (Ramelli et al, 2002) and the northern end of all these splays is truncated by the Washoe shear zone. In particular, there are three splays referred to in this report; there are several other smaller faults as well. The three faults referred to are the main fault trace near the base of the range, the Western fault within the range, and the Northern fault between the two.

The two secondary faults of the horsetail splay, the Western fault and the Northern fault, appear to be transitional between the Mt. Rose fault zone and the Washoe shear zone. Each of these intersects a fault that is thought to be a part of the shear zone; the Western fault intersects the Evans Creek Headwaters fault zone and the Northern fault intersects Angela’s fault.

Figures 14a, 14b, and 14c (next page). Three photographs with views to the west and southwest of the northern Carson Range. The top photograph shows Mt. Rose and the fault faceted dip-slopes of the Mt. Rose fault zone at the range front. The middle and lower photographs show the truncation of the facet and the Mt. Rose fault zone by the Washoe shear zone in the central part of the photograph. The stepping nature of the range front can be seen in the lower photograph.

Western Reno Basin Extensional System

A west-side-down normal fault has been proposed to explain the basin structure in western Reno and fault scarps that are mapped in southern Reno (Abbott and Louie, 2000; Ramelli et al., 2011; Cashman et al., 2012). This fault has been called the Virginia Lake fault zone (dePolo, 2009) and the Virginia Street fault (Cashman et al., 2012). For societal and other reasons this fault would be best renamed the "Reno fault zone" (plate 1). This fault zone has created the sub-basin modeled in western Reno (Abbott and Louie, 2000; Cashman et al., 2012) and tilted Tertiary and Quaternary sediments in western Reno (Trexler et al., 2012; Cashman et al., 2012). The known possible surface traces, subsurface traces, and subsurface projections on cross sections of this fault have been shown by Ramelli et al. (2011) and have been imaged by Stephenson et al. (2013). Historically, this zone has been considered a structurally complex northern extension of the Mt. Rose fault zone, but studies such as this one and the opposite side down indicate it is a separate zone. The fault zone goes through downtown Reno and might gain more respect as a potential hazard with Reno in its name.

The Reno fault zone would project just to the north, if not into, the Mt. Rose Pediment fault zone. Other faults to the west, such as the Wheeler Reservoir fault, may also accommodate some of this extensional deformation in the western Reno basin.

Northern Carson Range Section

The Washoe shear zone crosses the northern and northeastern flank of the Carson Range and this portion of the zone is called the Northern Carson Range section. Some additional related faults may also occur to the north in the adjacent part of the Reno basin (Briggs et al., 2015). The Northern Carson Range section can be further broken down into two parts, the Caughlin Ranch reach and the Ballardini Ranch reach, based on different structural patterns and different structural functions. The Caughlin Ranch reach is in the central part of the northern Carson Range front and is made up by at least two subparallel faults within the range front. In the Ballardini Ranch reach, the fault zone appears to be reactivating a network of preexisting faults. In this later reach the Washoe shear zone truncates the northern end of Mount Rose fault zone's horsetail splays within the range.

The northern Carson Range is made up of the Kate Peak Formation which is composed of Tertiary volcanic (andesitic and dacitic) and sedimentary rocks that are approximately 12 Ma old (Ramelli et al., 2011). The northern Carson Range is warped (c.f., Thompson, 1952) and dome-like in nature with dip-slopes on its eastern and northern flanks. The dips of volcanic foliation on these flanks range from ~25° to ~50° towards the valley (Ramelli et al., 2011). Additionally there has been extensive hot spring activity causing hydrothermal alteration of rocks and a small volcanic intrusion (Thompson and White, 1964; Bonham and Rogers, 1983; Ramelli et al., 2011). The hydrothermal alteration is extensive in the Ballardini Ranch reach and extends into the southern part of the Caughlin Ranch reach. Earlier faulting in the Ballardini Ranch section may have been related to post-12 Ma magmatic and hydrothermal activity.

The Northern Carson Range section of the Washoe shear zone is mostly formed in bedrock; there is very little Quaternary alluvium. The alluvium that does exist includes thin deposits along some of the lower gradient reaches of streams, colluvial slope deposits, and some pediment deposits in the lower part of the Caughlin Ranch reach. The bedrock is jointed and locally faulted.

Fault geomorphology appears to be poorly preserved in the mountains. High rainfall amounts, torrential storms, and steep gradients in the mountains can lead to fairly high erosion rates. In addition, the range front is periodically shaken by earthquakes, such as the 1914 Reno earthquakes and the 1948 Verdi earthquake, three nearby events of magnitude 6 or greater. As such, the preservation of geomorphic features in the mountains from relatively low slip faults is relatively poor. When sharp looking tectonic geomorphic features are visible, they are likely quite young. Other geomorphic features that are common, such as stream channels running along faults, naturally erode or bury tectonogeomorphic features. Lastly, geomorphic features that can be identified commonly have alternate possible explanations, such as differential erosion. Thus, the identification of the late Quaternary faults along this section was difficult, uncertain, and is likely incomplete. Large- and small-scale geomorphic features, mapped geologic faults, and the alignment of features were used to identify candidate fault traces.

Ballardini Ranch Reach

The Ballardini Ranch reach is one of the most complex parts of the Washoe shear zone, partly because it is the intersection of two significant faults and partly because there is a network of existing faults and areas of hydrothermal alteration in the Tertiary bedrock that are being reactivated by younger faulting. The northeastern-most part of the Carson Range has been shattered with faults resulting from the uplift of the range and volcanic activity. The two faults that intersect in this reach are the Washoe shear zone and the western branches of the Mt. Rose fault zone. Two fault zones in this reach are highlighted and herein named the Evans Creek Headwaters fault zone and Angela’s fault zone (named after a long time local rancher and a member of the Ballardini family). A third suspected fault zone, the Ballardini Ranch lineament, might go through the Ballardini Ranch area but was too uncertain to define. Many uncertainties remain with understanding the structural nature of this reach and knowing which faults have late Quaternary activity. LiDAR was only available for the easternmost part of the reach.

Several of the mapped faults have some indication of late Quaternary movement although in most cases it is unfortunately subtle. This evidence includes ponded Quaternary alluvium, side-hill benches, side-hill scarps, linear drainages, vegetation lineaments, springs, and spring alignments. This is a first cut on how the shear zone projects through the Ballardini Ranch reach. Other faults are along this reach of the zone are likely involved but there was not sufficient information found to suggest this at this time.

The approach to mapping faults in this reach was to consider the mapped faults, look for large scale geomorphology (escarpments, large lineaments), and to look for additional evidence of small scale geomorphic features, such as alignments of geomorphic anomalies, tonal and vegetation lineaments, fault scarps, linear drainages, and facets. Aerial photography, Google Earth, and limitedly available LiDAR were used to locate and consider features. I also conducted limited field examination.

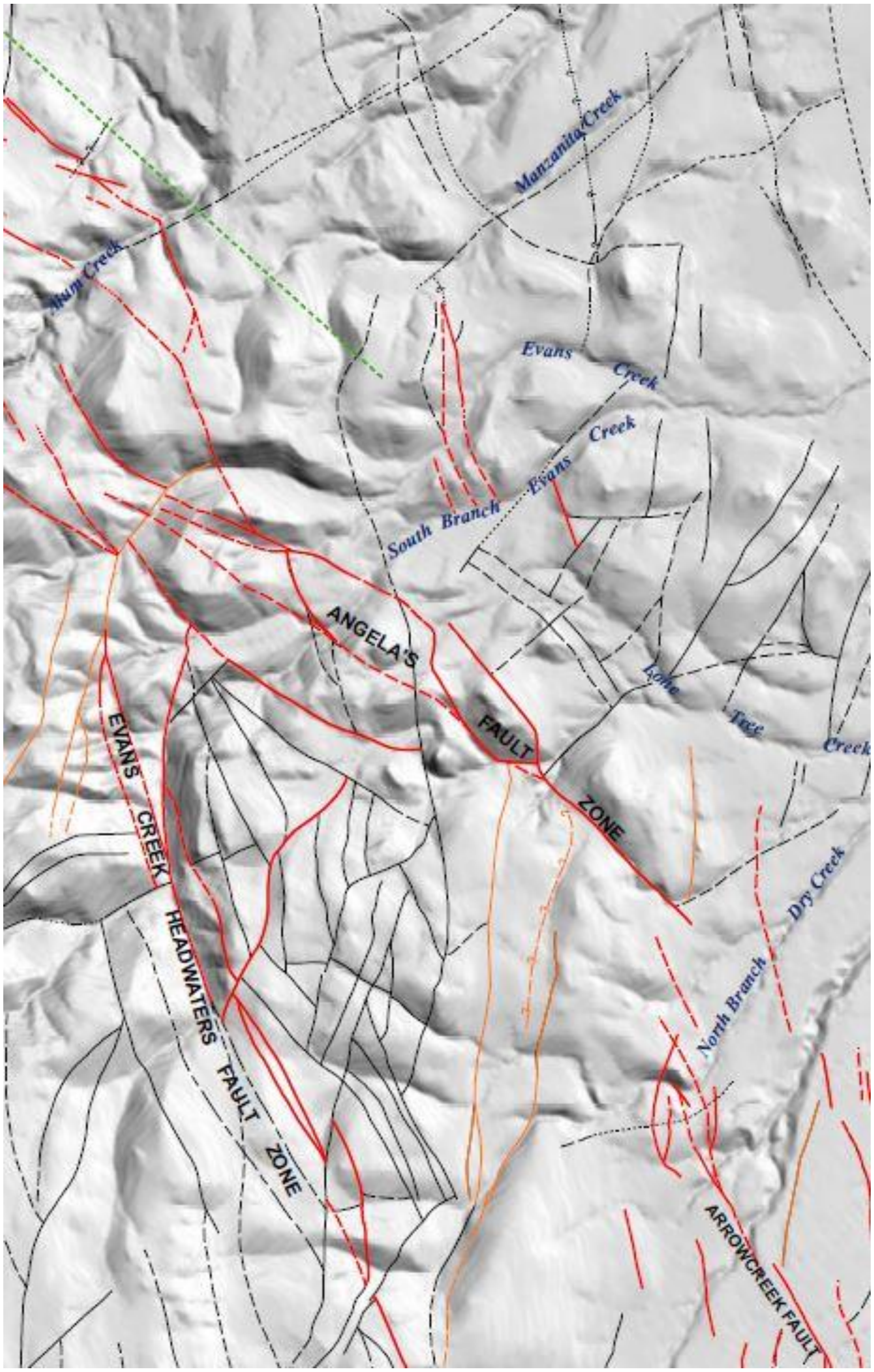


Figure 15. Potential Quaternary faults in the Ballardini Ranch reach. Red faults are candidates for a strike-slip component and orange faults are normal faults that may be part of the Washoe shear zone.

The structural pattern in the northeastern Carson Range is quite remarkable (c.f., Bonham and Rogers, 1983; Ramelli et al., 2011). It is made up of a network of faults that can be divided into several structural domains (fig. 16). I haven't studied these domains in detail nor in the field to gain insights into their tectonic and kinematic behavior. I have just made some general observations that give a first-order characterization of their map-view structure (Table 2). The point of Figure 16 is to show there is a domain that can be ascribed to the Washoe shear zone in the northeastern Carson Range that is consistent and aligned with the overall tectonics of the shear zone. Additionally, other neighboring domains have characteristics that are consistent with the interaction between the Washoe shear zone and adjacent faults. In the Ballardini Ranch reach, the Washoe shear zone is reactivating or creating(?) northwest striking faults, may be wrenching local networks of faults, and may be activating the boundary between domains 1 and 2 (Evans Creek Headwaters fault zone). In the Ballardini Ranch reach, hydrothermal alteration is mostly in domain 5, the domain with the main Washoe shear zone. Because domain 2 lies between the Evans Creek Headwaters fault zone and Angela's fault zone, one hypothesis for the structural pattern in this domain is an earlier or contemporary structural interplay between these two faults.

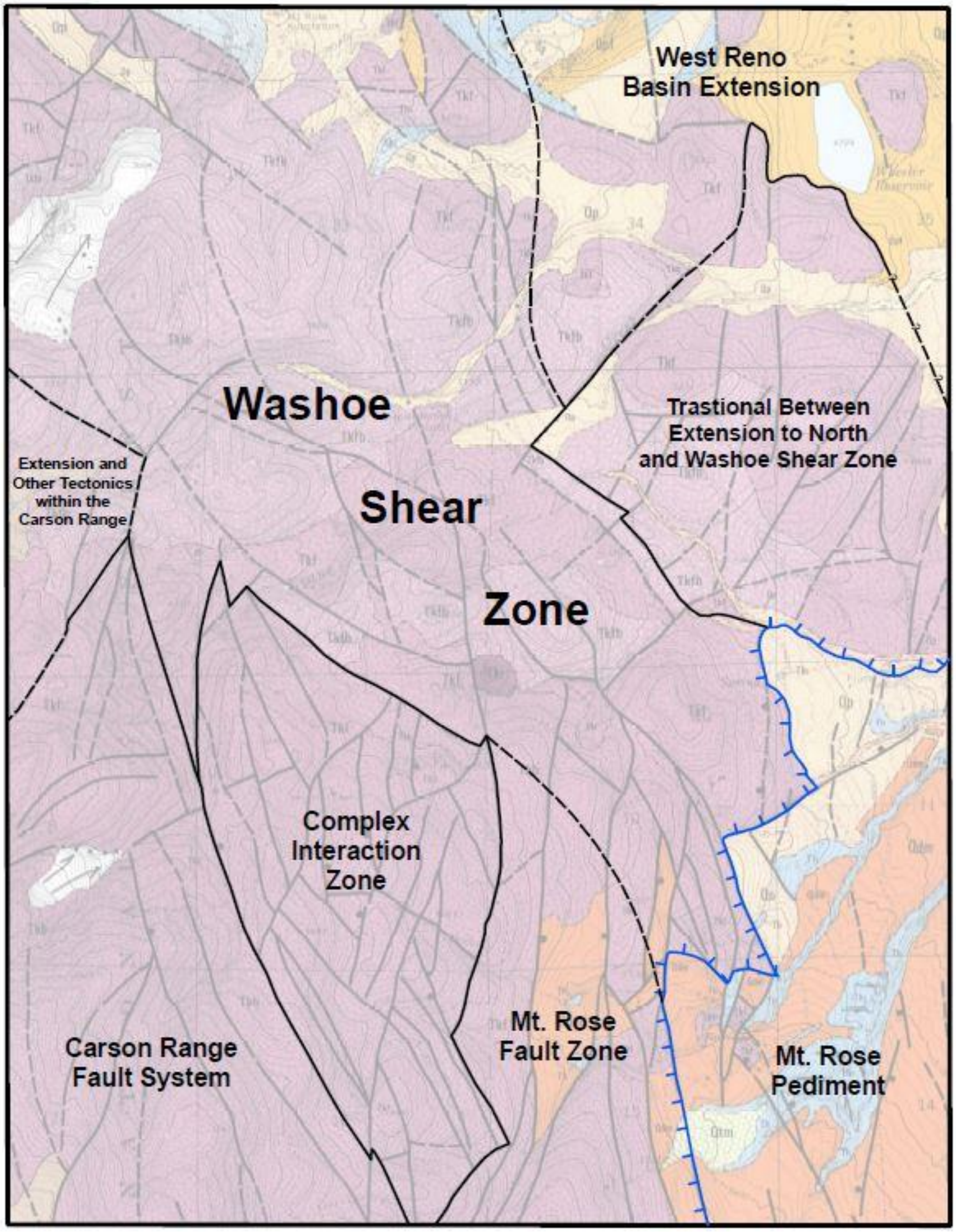


Figure 16. Structural domain map of the northeastern Carson Range and the Ballardini Ranch reach of the Washoe shear zone. The base is the geologic map of Bonham and Rogers (1983). By thinking in terms of fault orientation and fault density domains, the boundaries and structural interactions of the Washoe shear zone through this reach can be defined. The domains are characterized in Table 2. West boundary (long -119.8761 W), East (long -119.8158 W), North (lat 39.4630 N), South (lat 39.4194 N).

Table 2. Structural Domains in the Ballardini Ranch Reach of the Northern Carson Range Section of the Washoe Shear Zone.

Domain #	Affinity	Fault Strikes	Fault Cross-Strike Distance	Map View Intersection Angles	Fault Relationships
1	Carson Range fault system	NW, NE	0.2-0.6 km; closely spaced	low angle; some secondary faults high angle	subparallel faults; normal and right lateral(?)
2	range front extension; poss. earlier volcanic tectonics	NW, NE	0.1-0.25 km; very closely spaced	high angle	subdomains of sets of faults; normal faults
3	Mt. Rose fault zone	northerly	0.3-0.7 km; closely spaced	parallel main faults; secondary faults high angle	parallel synthetic normal faults
4	Carson Range internal deformation	northerly, NW	*	*	*
5	Washoe shear zone	NW & northerly	0.2-0.5 km; closely spaced	Low to moderate angle; few secondary faults high angle	faults commonly subparallel
6	Transitional between west Reno basin extension	NE; couple EW and few N	0.2-0.5 km; closely spaced	Low to high angle	faults are in sets
7	West Reno extensional system	N	0.5-0.7 km; closely spaced	main faults don’t intersect; secondary faults moderate angle	largest faults are parallel

* = not studied

Evans Creek Headwaters fault zone

The Evans Creek Headwaters fault zone is a north-northwest striking fault zone that was originally mapped by Bonham and Rogers (1983) and appears to be a transitional fault between the down-drop of the range along the Mt. Rose fault zone to the transtensional Washoe shear zone (Plate 2). The northern third of the Evans Creek Headwaters fault zone controls the location of a northwest-trending section of Evans Creek. This part of Evans Creek captures several drainages coming in from the highlands to the south. Any tectonogeomorphic features that might have existed along the drainage have been eroded away. Immediately southeast of Evans Creek, the fault forms a swale, lineaments, and a faceted hillslope (fig. 17). Other geomorphic features along this zone include: vegetation lineaments, a location at the base of faulted hillslopes, and aligned springs. The westernmost part of the fault zone is out of the direct erosional influences of Evans Creek and crosses along a bench in a hillslope.

Figure 17. Small faceted hill (left-center) with lineaments at its base. It lies along the eastern part of the Evans Creek Headwaters fault zone (lat. 39.4271 N; long. -119.8614 W). The headwaters of Evans Creek can be seen in the right third of the image. The fault facet is about 150 m high. View to the southwest of a Google Earth image.

The Evans Creek Headwaters fault zone is about 5 to 5.5 km long. The overall strike of the fault zone is N25°W. The north half of the zone dips northeast, whereas the southern half may have a steeper dip. The Evans Creek Headwaters fault zone is within the older Tertiary bedrock units (older than 18 Ma; Ramelli et al., 2011) and at least in one case a fault trace of the zone down-drops and juxtaposes undivided volcanic breccia rocks against undivided andesitic and dacitic rocks (Bonham and Rogers, 1983; Ramelli et al., 2011).

At its southeastern end, The Evans Creek Headwaters fault zone intersects the Northern fault of the Mt. Rose fault zone Midway the fault zone merges with the Western fault of the Mt. Rose fault zone. The northwest part of the Evans Creek

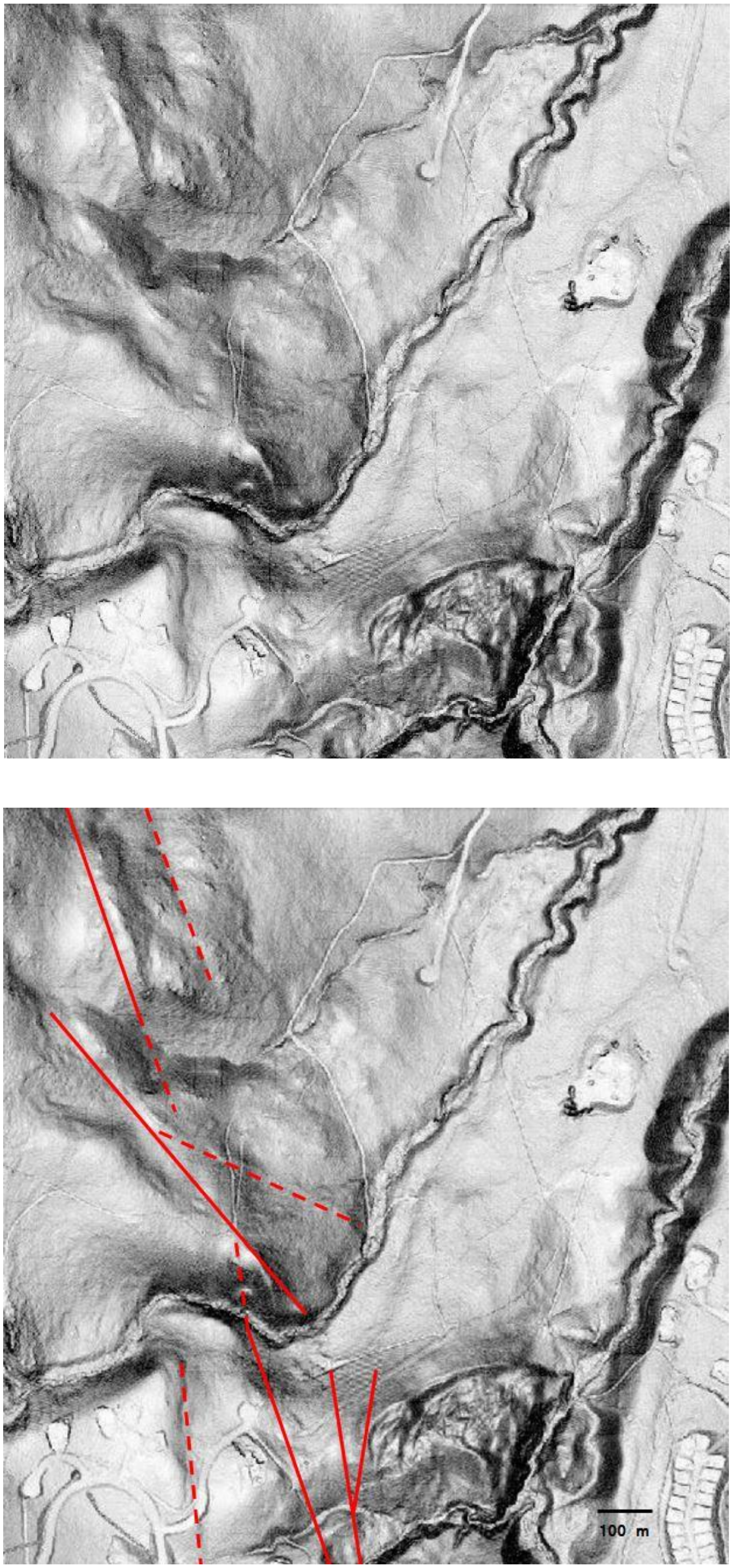
Headwaters fault zone connects with Angela's fault zone. Along the northern part of the fault zone it has a significant normal dip-slip component. A possible surface offset of roughly 230 m vertical separation was estimated in the central part of the fault zone (lat. ~39.437 N, long. ~119.862 W). The southern half of the fault zone appears to have significantly less of a vertical component. A small lateral component for the entire zone is inferred from the orientation of the fault, but no specific lateral offsets were seen on imagery. Several cross faults from domain 2 intersect the Evans Creek Headwaters fault zone. These secondary faults both cross and are truncated by the fault zone.

Angela's fault zone

Angela's fault zone is an approximate continuation of the Arrowcreek fault of the Mt. Rose Pediment section (Plate 2). It provides a connection through a series of faults to the main faults of the Caughlin Ranch section. Angela's fault zone is entirely within the northern Carson Range. The geomorphic expression of late Quaternary fault activity is discontinuous and only weakly to moderately well developed, limiting confidence in the details of the zone. Nevertheless, there is a general alignment of geomorphic anomalies that appear to bear the zone out. Planned LiDAR for this area will likely help sort out the traces of Angela's fault zone better and make more secondary fault traces and structural relationships recognizable.

Angela's fault zone is about 6 km long and has on overall strike of N50°W. Fault traces within the zone have dominantly normal dip-slip movement, but given their northwest orientations, there is likely a secondary right-lateral component. The down-thrown side varies from fault trace to fault trace and is either down-to-the-northeast or down-to-the-southwest. Angela's fault zone is formed at the surface in volcanic rocks, volcanoclastic sandstones, and hydrothermally altered rocks of the Kate Peak Formation. The fault zone mostly lies within geologic units, but in one case it juxtaposes Tertiary andesitic rocks against volcanic breccia. About half of the fault zone is in hydrothermally altered rocks.

The southeastern end of Angela's fault zone is in the foothills of the northeastern Carson Range, immediately northwest of the end of the Arrowcreek fault. Along the western edge of the Mt. Rose pediment is the west branch of Dry Creek and this effectively separates these two faults. This stream channel may have on the order of 10 to 20 m of right-lateral offset across it, but the channel is irregular and the straighter sections are not parallel, so this is general approximation of the offset. Only one fault trace appears to be continuous between the Arrowcreek fault and Angela's fault zone - other related faults form a zone between the two (figs 18a and 18b). In the eastern flank of the Carson Range above the Arrowcreek fault is a small side-hill bench with a back-facing bedrock scarp (southwest facing) along a short northwest-striking fault. The hillslope above the fault appears to be locally destabilized and sliding in places. Along one part of this fault is an equivocal northeast-facing alluvial fault scarp on the range front side of the swale created by the back-facing ridge; the scarp is about 0.5 m high. The fault zone appears to step to the right as it transverses obliquely up the hillside where it merges with a mapped normal fault at the base of a small, southerly facing, faceted hill (fig. 19). There is a small, thin deposit of alluvium backing up at the base of the hill that appears to have been tectonically ponded (fig. 19). Here the fault is the contact between Kate Peak Formation volcanic rocks and volcanic breccia's. Also in this area, the northern fault of the Mt. Rose fault zone intersects Angela's fault zone.



Figures 18a and 18b. LiDAR image of the intersection of the Arrowcreek fault and Angela’s fault zone. Upper image is the LiDAR image and the lower image has schematic faults drawn on it, dashed where they are inferred. North is towards the top of the figure. LiDAR image provided by Courtney Brailo of the Nevada Seismological Laboratory.

Figure 19. Google Earth image with a view towards the west of the faulted hill with Quaternary alluvium gathered at its base. Angela's fault zone comes through near the base of the hill, then splits around the hill that can be seen in the upper third of the image. The facet in the fault hillslope in the foreground is 43 m high, so there is vertical exaggeration in this image. Also note that the color changes are photo stiches – the image was chosen because it showed the hillslope and fault well.

The fault zone continues to the northwest along northwest-striking faults. These split around a small hill. One fault trace is mapped around the northern flank of the hill, but appears to be dying out and stepping south to the other trace. The most active fault trace goes along a linear drainage (modified fault scarp?) on the south side of the hill. This channel appears to be oversized for its drainage area possibly due erosion along the fault. The fault splits near the west side of this drainage with the southern trace continuing up and over the hill and the northern trace going through a small saddle. The northern trace continues down the base of a hillslope towards the south branch of Evans Creek. The southern trace continues down the western flank of the hill towards the creek as well. Along the west side of the south branch of Evans Creek there is a late Pleistocene alluvial terrace in this area (Ramelli et al., 2011). This terrace is partly alluvial and partly strath in character. Where the southern trace crosses the terrace, it has been eroded out into a linear drainage following the fault. Where the fault crosses, the stream channel has a right lateral jog of about 45 m.

Where the northern trace of Angela's fault zone crosses the terrace there are swales and an eroded fault scarp along it (figs. 20a and 20b). This fault continues to the west, splits into two parallel faults, and is mapped up a small valley. West of this, the northern trace changes to a more northerly strike and crosses the base of a bench in a hillslope just east of Alum Creek. There are a couple lineaments around Alum Creek that are candidates for connecting Angela's fault zone to the Caughlin Ranch fault and/or the Crest fault zone of the Caughlin Ranch reach.

The disruption of the late Quaternary terrace along the south branch of Evans Creek demonstrates late Quaternary activity along Angela's fault zone.

There is one other fault trace that is part of Angela's fault zone. This trace begins at an dacitic intrusive body and trends to the northwest. This fault is in part the contact between pre-18 Ma and younger volcanic rocks. This southern trace crosses the terrace along the south branch of Evans Creek very close to the southern end of the terrace, where the terrace appears to be in fault contact with the adjacent hillslope. In this area, faults from the Evans Creek Headwaters fault zone intersect Angela's fault zone and it is structurally connected by faults to the other traces to the northwest.

Ballardini Ranch Valley

The Ballardini Ranch valley has possible late Quaternary structures in it, but it is too speculative to infer this on a map at this time. The irrigated fields of the Ballardini Ranch are in a small valley that is behind, or south of, a small hill at the northeastern-most tip of the Carson Range. Northwest-striking bedrock faults have been mapped through the valley by Thompson and White (1964), Bonham and Rogers (1983), and Ramelli et al. (2011). There are some lineaments, such as a northwest-trending shallow swale in the eastern part of the valley that are targets for future investigations. Streams coming down from the highlands above are captured in this valley (except for the southern branch of Evans Creek on the westernmost side). This small valley has been ranched, farmed, and hunter/gathered for decades and there are many lineaments that can be attributed to human activity. These include irrigation ditches, irrigation contrast lines, fire burn lines, and old weathered roads and trails. A nontectonic alternative for the formation of this small valley would be differential erosion. The valley is mostly underlain by hydrothermally altered rocks versus unaltered rocks on the bounding hillsides.

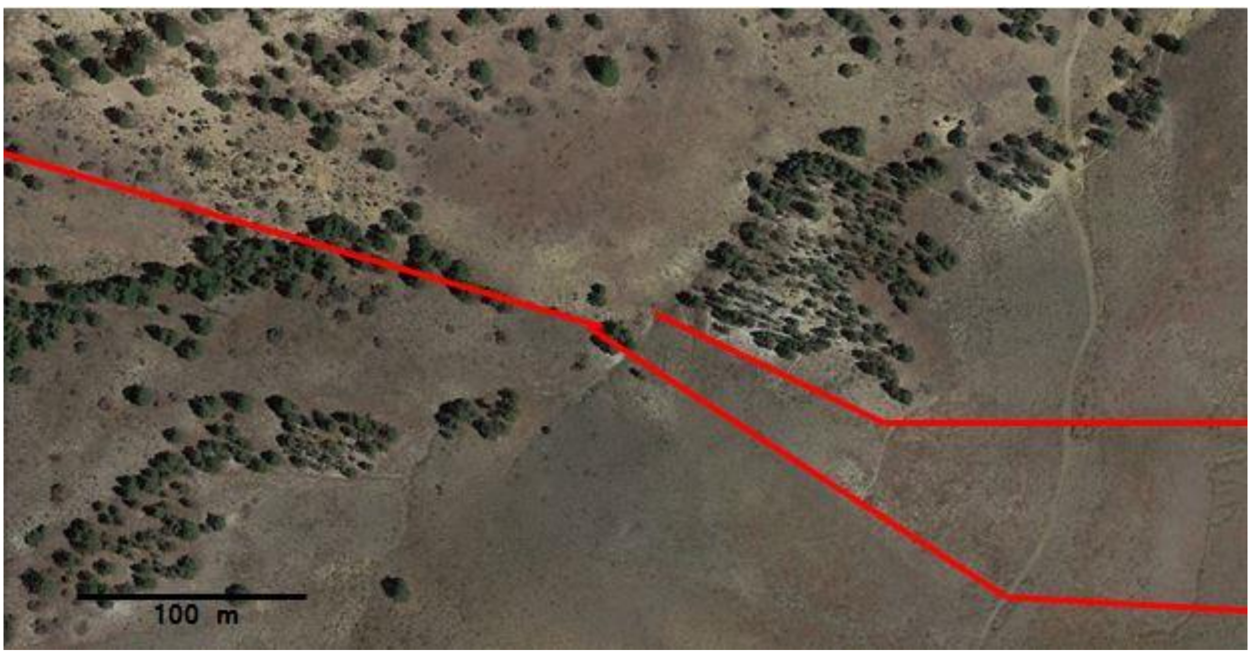


Figure 20a and 20b. Area where the northern trace of Angela's fault zone crosses the terrace along the south branch of Evans Creek (not visible). The lower image shows schematic fault traces. The terrace is in the lower right quarter if the image and is indicated by Ramelli et al. (2011) to be late Quaternary, thus the fault is late Quaternary. This is an oblique view of a Google Earth image and north is towards the top.

The is some evidence that a northwest-striking, vertically dipping fault in the eastern part of the Ballardini Ranch area was active during the hydrothermal period of the northern Carson Range, or that was used by hydrothermal fluids. It is a linear siliceous deposit that stands out on the landscape due to differential erosion. The deposit is located north of Lone Tree Creek (lat. 39.4523 N; long. -119.8250 W). It is about 35 m long and has a strike of about N70°W. There is a linear drainage parallel to and southeast of this deposit that was one of the features considered as a possible Quaternary fault.

A small set of faults immediately northwest of the Ballardini Ranch valley has some faults that may have associated fault scarps. These three parallel faults are between Evans Creek and the south branch of Evans Creek (plate 2). These faults are just beyond the southeast end of the 2008 geodetic lineament of Bell et al. (2012). They all cross Evans Creek to the northwest and cross the steep flank of a small hill that has a disrupted appearance. This may be a secondary fault along the edge of the shear zone or may connect to faults to the northwest.

Volcanic Activity

A few episodes of late Neogene volcanism have occurred proximal to the Washoe shear zone in the northern Carson Range. The oldest volcanic center was a dacite intrusion mapped by Bonham and Rogers (1983) as part of the Kate Peak Formation (locally dated at 12.26 Ma by Ramelli et al., 2011). This volcanism may have been associated with the hot spring activity at the northern Carson Range, evidenced by the mineralized and altered Kate Peak Formation deposits. The small intrusive body appears to intrude both hydrothermally altered and unaltered Kate Peak Formation rocks at a boundary between these two. Thus, the intrusion is likely younger than the 12.26 Ma date. Youngest basaltic volcanism occurs just to the south in the Carson Range as evidenced by lavas dated at 1.4 Ma and 2.5 Ma by Cousens et al. (2011).

Caughlin Ranch Reach

The Caughlin Ranch reach of the Washoe shear zone is located in the central part of the northern front of the Carson Range. The range front is made up of Tertiary volcanic and sedimentary rocks that are moderately tilted to the north (Thompson and White, 1964; Ramelli et al., 2011) forming a relatively steep escarpment. The boundaries of this reach are somewhat arbitrary, but are near the ends of the faults within it. Alum Creek is considered the southeastern boundary with the Ballardini Ranch reach. The northern boundary is set in the hills just south of the Truckee River. In the western part of the reach, softer, Hunter Creek sandstone has been uplifted into the range front and it is difficult to identify and map out tectonogeomorphic features. In this area, faults from the adjacent Mogul-Verdi section project south of the river into the hills, making this a bit of a fuzzy boundary. The characteristics of the Caughlin Ranch reach are late Quaternary faults within a steep range front with moderately dipping geology (fig. 21). Activity along these faults is potentially destabilizing the range front in places. The 2008 geodetic lineament of Bell et al. (2011) is located at the base of the range in the Caughlin Ranch reach. Although not definitive, this may indicate there is a buried tectonic feature near the base of the range.

The main faults identified along this reach are the Caughlin Ranch fault and the Crest fault. South of these, there are a couple other subparallel faults inferred within the range and there are a number of secondary faults mapped throughout the reach as well. There is also a possible buried fault at the base of the range.

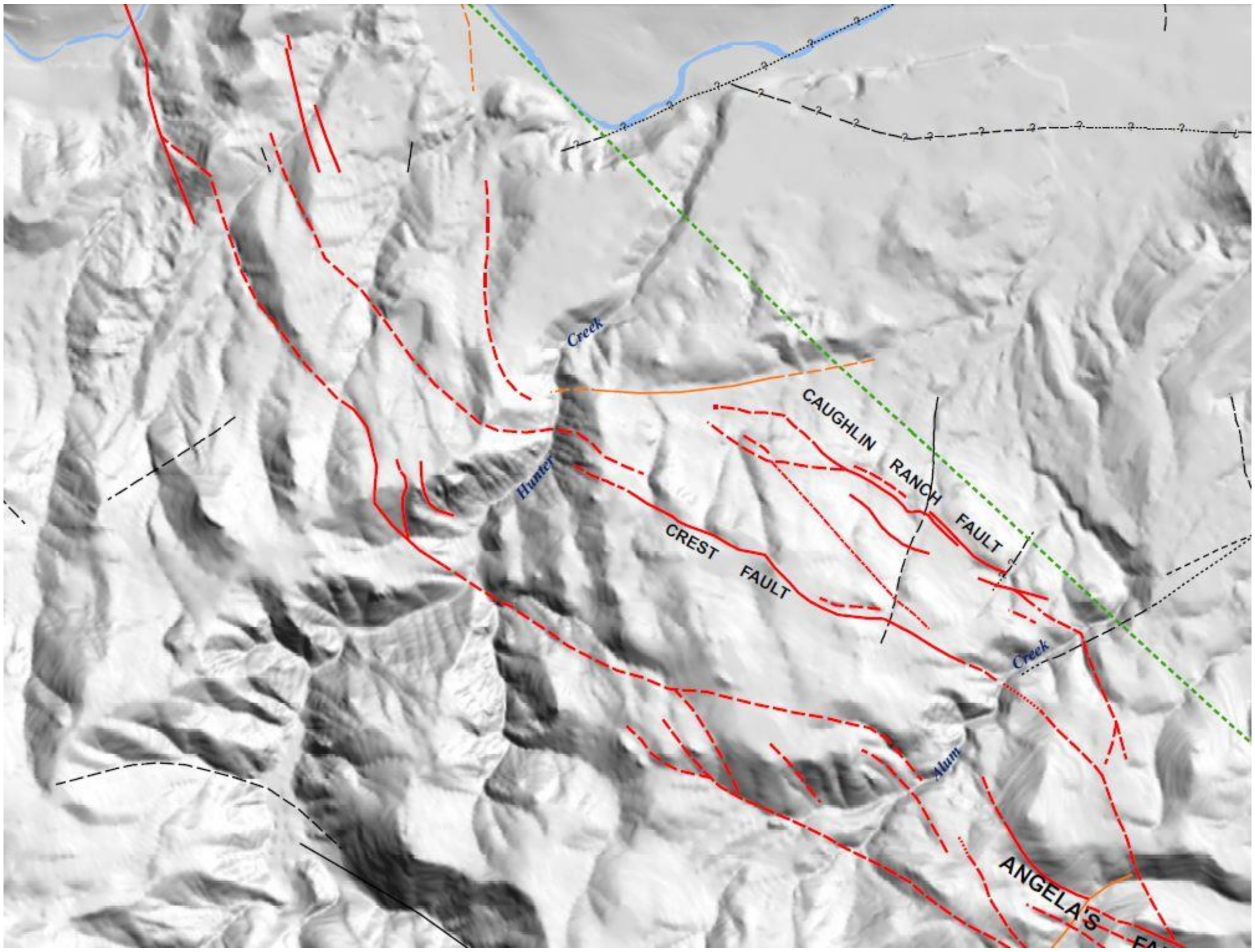


Figure 21. Faults that are part of the Caughlin Ranch reach. Section of Plate 3. North is towards the top of the figure. Red faults are candidates for having a right-lateral strike-slip component. The green dashed line is the 2008 geodetic lineament of Bell et al. (2012).

This reach of the shear zone appears to be influenced by both tectonic and gravitational forces. The range front seems to be wrenching between the two main fault traces, the Caughlin Ranch fault and the Crest fault. Part of the range front in between the two northern faults may be collapsing with a few panels of range front sliding down. The panels would be sections of dipping volcanic rocks that are possibly sliding down on bedding planes. An end-member interpretation is that the faults and deformation are solely related to uplift of the Carson Range, over-steepening of the range front, and subsequent collapse; in this end member fault scarps would be created by the collapse, not necessarily earthquakes. A few observations indicate, however, that tectonism is likely involved in this range-front deformation. First, the range front deformation is confined between two faults and does not continue to the base of the range front itself. Thus, movement on the faults appears to be driving and confining the range front collapse. Second, the main faults continue beyond the collapsed area. Third, there appear to be elements within the collapsed area that are not perpendicular to the “down direction” of the range front, but are at a slight angle to it and have been influenced by wrenching. Lastly there don’t appear to be any visible "toes" of landslides near the base of the collapsed area. Geologic contacts near the base of the range front, such as the contact between the Kate Peak Formation and the Hunter Creek Sandstone appear to be in place and are not distorted, other than being offset by faults locally (Ramelli et al., 2011). These observations support local extension driving (and swallowing) the failing area. The Caughlin Ranch fault and a normal dip-slip fault to the immediate south are at the base of the collapsing area and this internal transtension within the range front appears to be inducing the range-front collapse. Insight might be gained by understanding the lineament in Figure 22 better, including the dips of the faults that are likely creating it. For example, it is possible they dip back into the range.

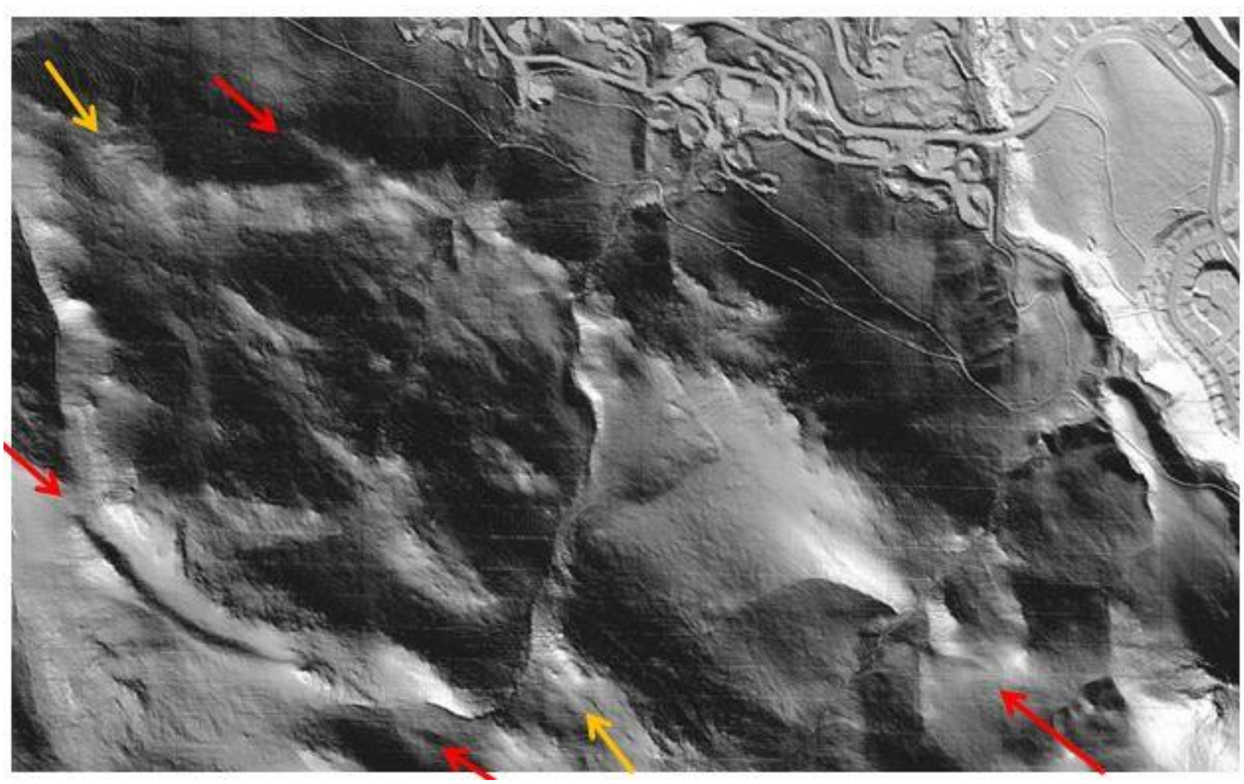


Figure 22. LiDAR image of the northern Carson Range front showing the Caughlin Ranch fault (between the upper red arrows), the Crest fault (between the lower left two arrows), and prominent lineament between these two faults (between the orange arrows). The Caughlin Ranch fault is fairly linear but has a left-stepping character to it. Illumination is from the southwest.

Caughlin Ranch fault

This study was initially focused on the northwest-striking Caughlin Ranch fault (herein named), which has fault scarps and a remarkable continuity over about 1.8 km within the northern Carson Range front (plate 3; fig. 21). This fault has been walked out; hand trenched; and mapped using aerial photography, Google Earth, and LiDAR imagery. Although seismic hazard parameters were not able to be directly determined, late Quaternary activity of one fault trace has been established. This is the trace that was hand trenched but is in a complication in the fault zone, creating a reverse fault. Alternatively the work needs to be done to rule out a slide plane related to the range-front collapse or any other gravity feature.

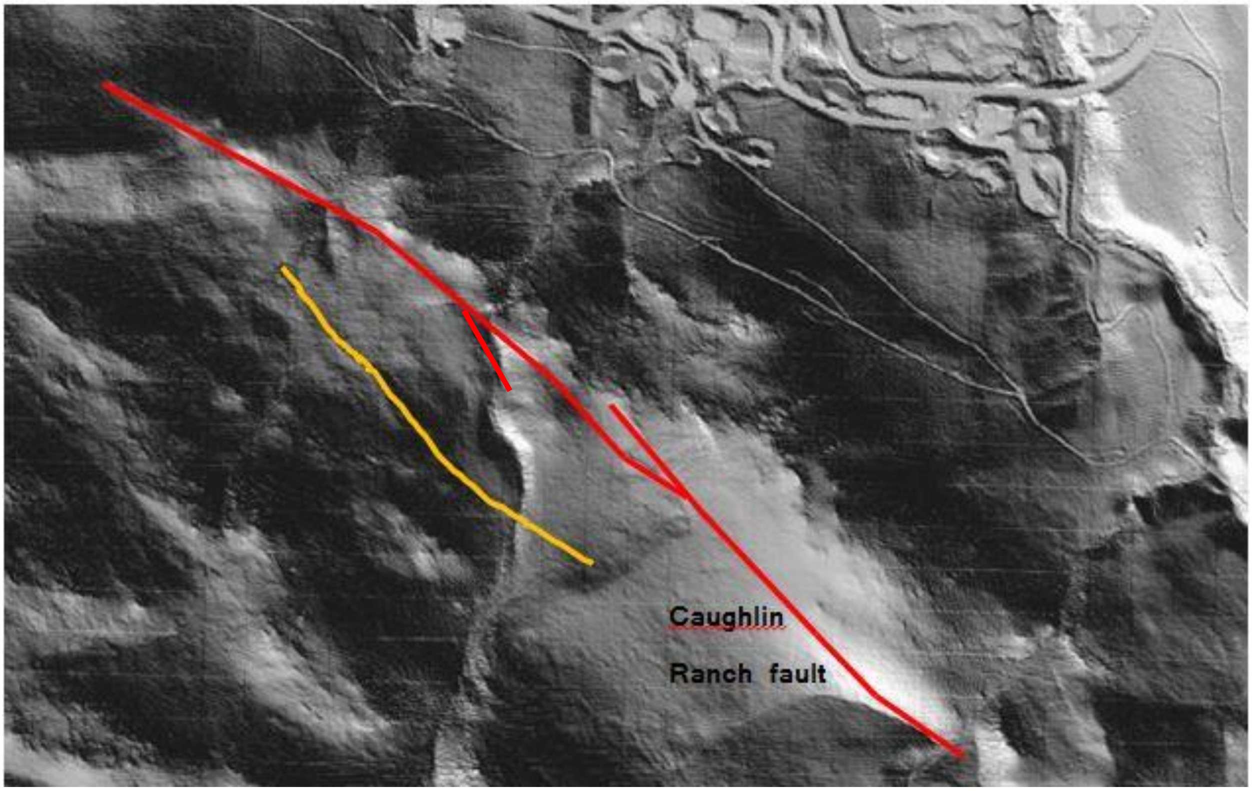
Along the Caughlin Ranch fault, a bench has formed in the range front (fig. 23), in which a Quaternary pediment has developed on moderately northward-dipping Miocene Kate Peak Formation rocks (lava flows, sandstones, altered volcanic rocks). Quaternary alluvium is limited to thin (≤1 m) pediment deposits and as discontinuous thin, bouldery alluvium within incised channels that cross the bench. Much of the Quaternary deposition on the range front, including within the bench, is ephemeral. In the bench area, there are some colluvial slopes and pediments away from the drainages that have some older alluvium on them, which may be useful in landscape reconstructions. The Caughlin Ranch fault is along the northern side of this bench and there are secondary normal dip-slip faults within and along the southern side of the bench.

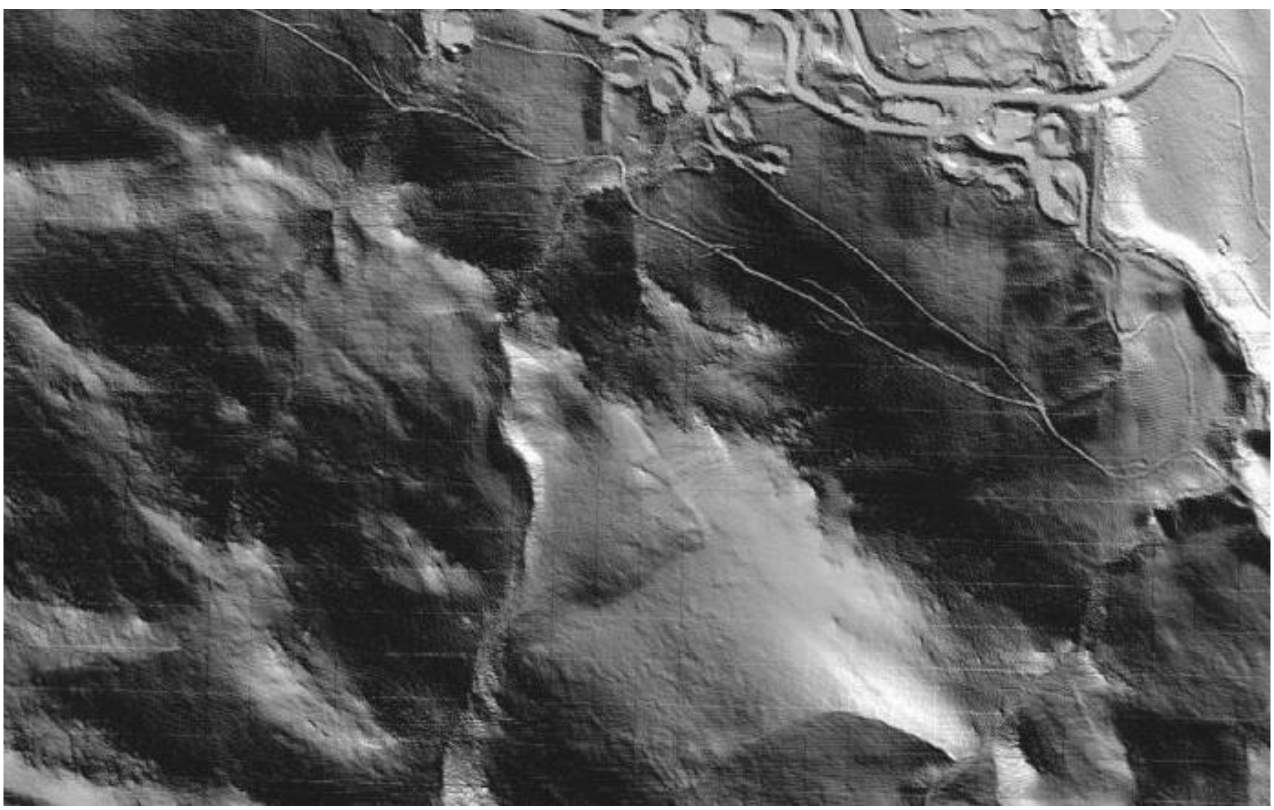
Figure 23. View south-southeast of the northern Carson Range showing the bench in the range front (center and left-center) where the Caughlin Ranch fault comes through. Google Earth image.

The Caughlin Ranch fault is a relatively straight, normal fault with a likely component of right-lateral strike-slip. The fault is 1.8 to 2 km long, appears at the surface in a 40 to 50 m wide zone, and has an overall strike of N55°W. The southeastern end likely links up to Angel's fault zone and the northwestern end appears to step to the south along a secondary normal fault. Geomorphology along the fault includes single-event and compound fault scarps (fig. 24), side-hill benches, sharp and even northwest-trending aligned bedrock alluvial contacts, and a trend across the landscape of an even, very low inflection that is shown on LiDAR as a lineament of even luminosity (figs. 25a and 25b). Single-event fault scarps are about 0.5 m high and the largest compound scarp is 10-m high. The continuity, nature, and straightness of the geomorphic features indicate this is a fault zone rather than a local feature related to other processes. In this environment, it could also indicate the most recent event was fairly young.

Figure 24. Fault scarp of the Caughlin Ranch fault crossing the north side of the bench in the northern Carson Range front; view to the west. A latest Quaternary 0.5- to 1-m-high fault scarp can be seen crossing the landscape between the arrows. It goes down into the gulley and back up the shoulder to the farthest arrow.

The downthrown side of the Caughlin Ranch fault is a little mixed. Overall the back-slope-facing (southwest-facing) low ridge along the northeast side of the Caughlin Ranch fault indicates down-to-the-southwest movement; this contact is the approximate contact between the volcanic and sedimentary rocks of the Kate Peak Formation in places, so there may be some differential erosion in this apparent offset signal. Fault scarps, the compound scarp, and the eastern side-hill-bench appear to be dominantly down-to-the-northeast, however. Thus, the most recent activity appears to be valley-side down. This doesn't seem like it could be the long-term sense-of-movement though because the back-facing ridge would be down if so, unless there wasn't any down-to-the-southwest movement and differential erosion was able to keep up with and exceed tectonic movement. The most recent event along the fault was down-to-the-northeast, and I would assume that for the next event.

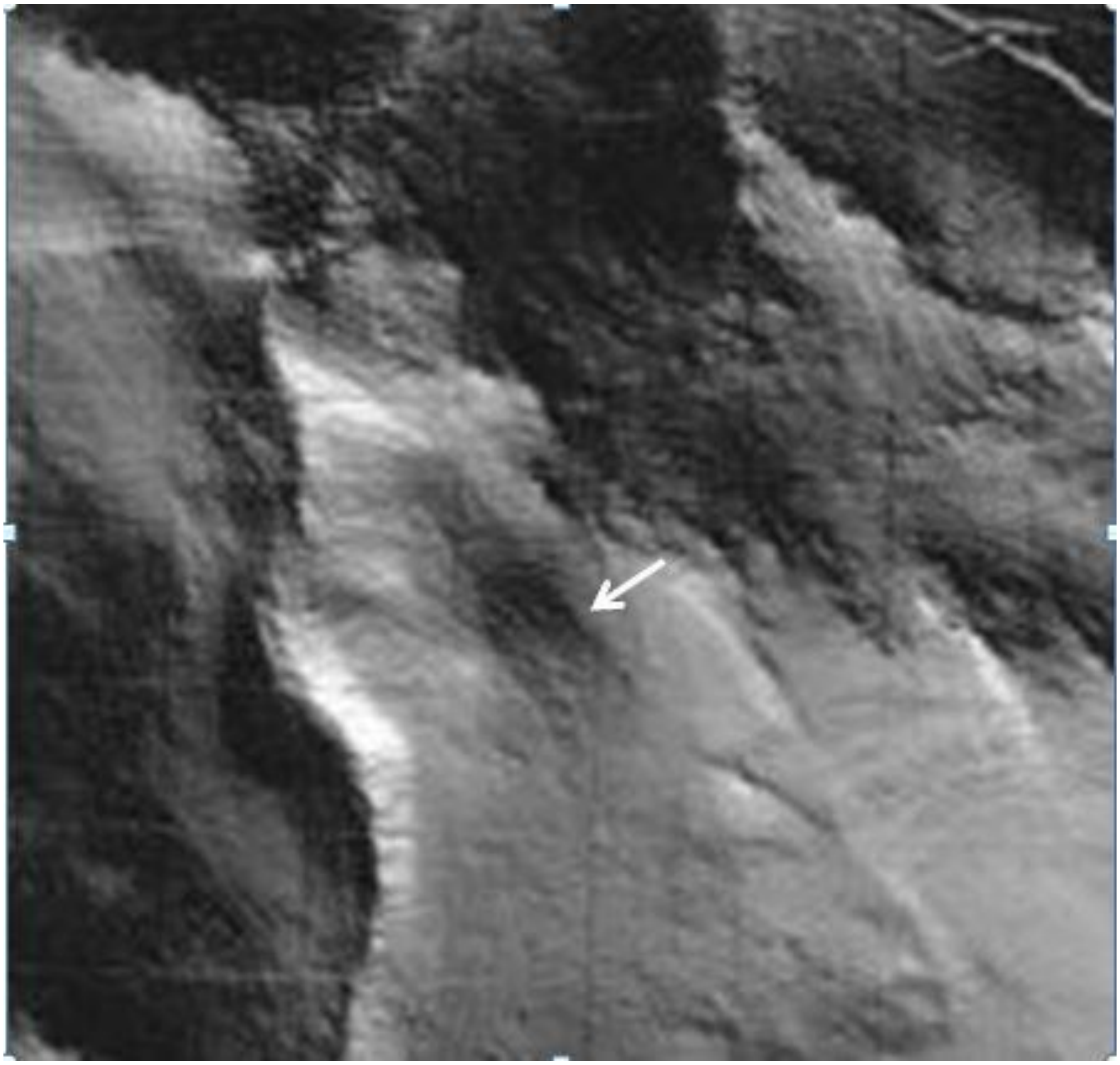




Figures 25a and 25b. LiDAR imagery with a southwest illumination that shows some features of the Caughlin Ranch fault. The above figure shows the main trace of the Caughlin fault (red) and a nearby down-to-the-north normal fault (orange). North is up.

Initially the plan of this research was to dig a soil pit into a terrace with a compound fault scarp formed in it (figs. 26, 27, and 28), with the objective of developing constraints on a vertical fault slip rate of the Caughlin Ranch fault. While digging the soil pit it was discovered that the terrace was a strath terrace on Tertiary sandstone bedrock, however, and there were no significant alluvial deposits or stable soils that could be used to estimate the age of the terrace; there is alluvium exposed in the stream cut along this terrace, which is why it was originally targeted. That must be confined along the stream channel and does not appear to be on the relatively stable top of the terrace.

Figure 26. Trench 1, visible at the base of a 10-m-high fault scarp; view to the south. The fault is between the red arrows. Trench 1 is just above with the orange arrow. The strath terrace has been labeled. The soil pit was just to the right of the word “Terrace”. Google Earth image.



Figures 27. Enlargement of the LiDAR image over Trench 1, indicated by the white arrow in the top image, on the Caughlin Ranch fault.

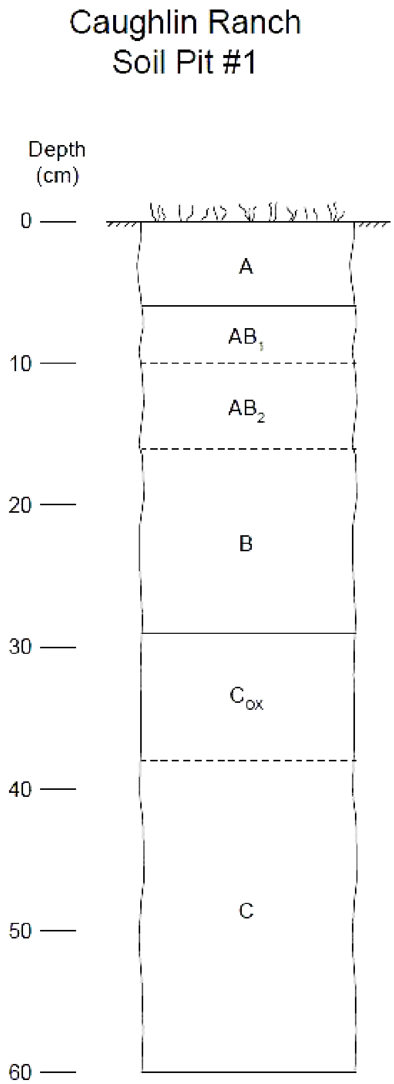


Figure 28. Soil pit from a strath terrace in the bench area of the northern Carson Range (lat. 39.4816° N; long. -119.8754 W). This pit was dug in an eroding 10° sloping flat surface that was deemed the best available on the terrace that was originally thought to be an alluvial terrace. The "A" horizon was brown loose single-grain pebbly sand; "AB_1" was similar to the A horizon but was moderately indurated; "AB_2" was a pebbly sand with more pebbles than above and pieces of lower horizons within it (B & C_{ox}); "B" was a pebbly sand with smaller pebbles, clay skins on clasts, and some clay bridges - the B horizon was moderately indurated but does not effervesce with HCl (nor does any other horizon) and breaks into small peds; "C_{ox}" is reddened, Fe-stained Tertiary sandstone; "C" is gray Tertiary sandstone of the Kate Peak Formation and was the parent material for the lower horizons. The soil is interpreted to be a relatively young soil (probably Holocene), likely much younger than the surface. This environment may strip off the soils periodically and start over with a thin alluvial flood deposit. Because this finding could not be used to solve the original slip rate estimate, this work was discontinued.

To confirm a fault origin and look for the most recent event of the compound fault scarp in the terrace, a hand trench was dug across the over-steepened base of the compound fault scarp (Trench 1; lat. 39.4818°, long. -119.8750; figs. 26, 29, and 30). The trench was effectively in bedrock and was difficult to pick and shovel into a trench, limiting the extent to which it was dug. Trench 1 revealed a mantling colluvial deposit with a mollic epipedon formed in it overlying faulted Kate Peak Formation sandstone. The hanging wall was sheared and broken up sandstone, whereas the footwall was more competent sandstone. A reverse fault with a strike of N30°W and a dip in the trench of 15° south was found between these units. As can be seen in Figures 29 and 30, the fault is a thin feature in the south part of the trench exposure but widens to 25 cm wide damage zone at its northern end in the exposure, where it would be coming to the surface. This damage zone has been faulted over a thin (10-20 cm thick) older, gray-brown colluvial deposit. This overriding of the older colluvium by the upper plate represents the most recent event and is estimated to be late Quaternary.

Trench 1 revealed a late Quaternary slip surface that is interpreted to be a reverse fault trace in the Caughlin Ranch fault (figs. 29 and 30). Most likely this reverse fault is the result of complications in the surface trace of the fault (it is near a left step in the fault), but the apparent range front collapse is occurring close to this location and something akin to a relict toe of a landslide cannot be ruled out without further work. Another small hand trench was initiated to the west along a smaller scarp, but this was not completed and has not revealed a fault yet. If further trenching is done I would work to the east of Trench 1 along the LiDAR lineament. An excavator trench would be ideal of course and there are many targets in the bench area. Because this older colluvial deposit is limited in extent and I wanted to preserve it, work was suspended on the trench until a better confidence in the origin of the fault could be gained.

Figure 29. Photograph of the eastern side of Trench 1 showing the reverse fault; view to the south, Note in the lower left-hand corner of the photograph the surficial dark brown colluvial deposit is underlain by a thin, lighter grayish brown colluvial deposit that is older, is involved in the damage zone of the fault, and predates the most-recent-event.

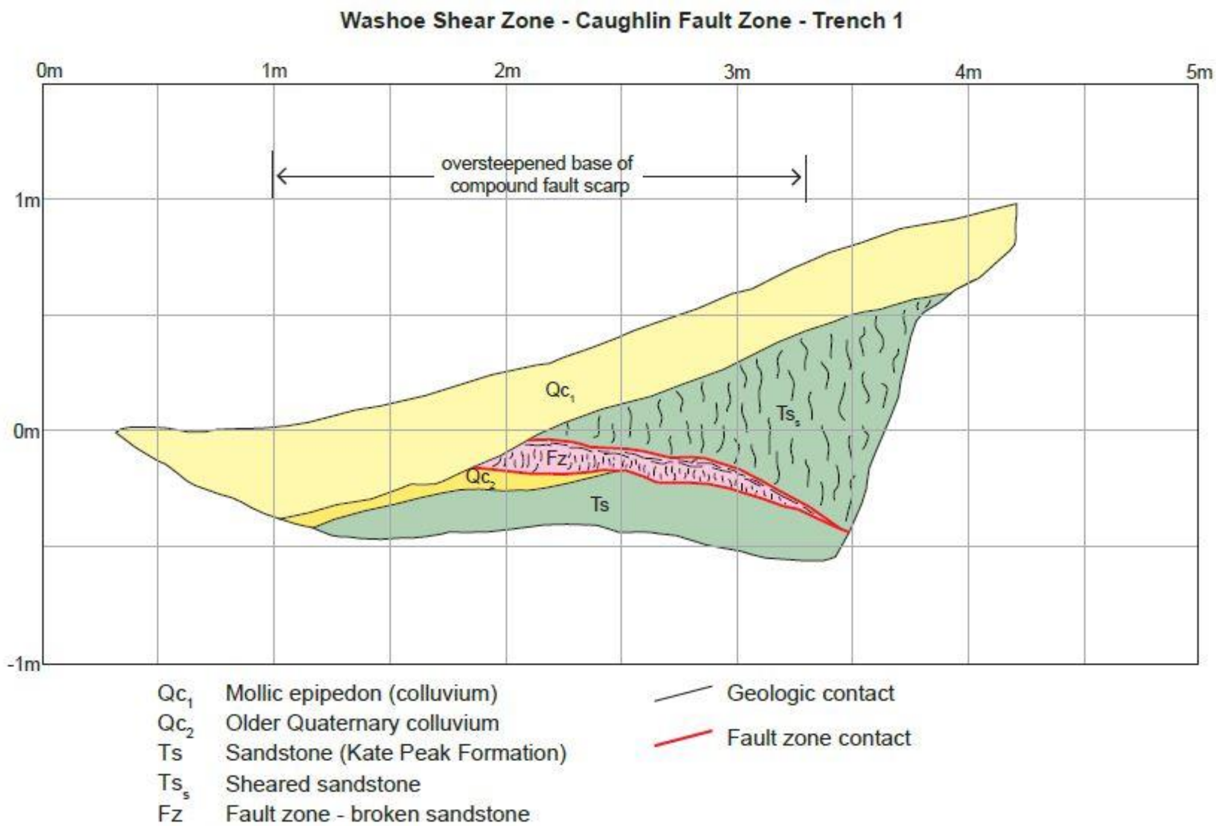


Figure 30. Hand trench dug into the toe of a 10-m-high compound scarp formed on the front of a strath stream terrace. The trench was oriented N40°E and the southeast wall is shown. At the southwestern end of the trench the fault was oriented N30°W and was dipping to the south 15°. The age of the older Quaternary colluvium is likely late Quaternary.

Crest fault zone

The Crest fault is near the top of the frontal escarpment of the northern Carson Range, above and southwest of the Caughlin Ranch fault (Plate 3; fig. 21). The Crest fault was initially examined by USGS scientists because of its relatively strong geomorphic expression and because there is an alluvial fault scarp in the western part of the fault. The fault is about 2.2 to 4.3 km long and has potential fault linkages with faults to the southeast in the Ballardini Ranch reach and a possible extension to the northwest. At the surface, the fault zone is 20 to 60 m wide in expression and the overall strike is N64°W. The Crest fault appears to be a dominantly normal dip-slip fault with the northeast side down over most of its length, but at times it is near the base of a southwest facing escarpment, suggesting the opposite down side, similar to the Caughlin Ranch fault. Given its orientation, there may be a right-lateral component as well. An arcuate graben along the Crest fault may have a wider west side than east, which might have been caused by a right lateral component. Tectonogeomorphic features along the Crest fault include a fault scarp, swales, vegetation and tonal lineaments, springs (fig. 31), an arcuate graben (32a and 32b), and disturbed slopes.

A gravity origin, or Sackungen, hypothesis needs to be entertained given the mountain crest position of the Crest fault, especially the part of the zone that is expressed as a broad arcuate graben. McCalpin (1999) laid out a fault height to fault length criteria for distinguishing tectonic faults from purely gravity features; the dividing criteria was a height to length ratio of 10 (McCalpin, 1999). Gravity features tend to be short and have large offsets relative to their length whereas tectonic faults are the opposite, with ratios that are smaller than 10. The Crest fault has a ratio that is much smaller than 10, suggesting it is a tectonic fault.

Figure 31. Vegetation lineament of springs along the Crest fault. View to the west on Google Earth image.

Figures 32a and 32b. Crest fault zone. Top: View west along the fault with the curvilinear "graben" in the foreground. Bottom: Side (westward) view of this feature. Google Earth images.

Other Inferred Faults

There appear to be some other northwest-striking fault traces along this reach that are inferred based on steps in the topography with vegetation and lineaments near their base (Plate 3). These faults are southwest of the Crest fault. They have not been visited in the field and confidence is moderate that they are late Quaternary faults, but they potentially contribute to the continuity of the Washoe shear zone, especially projections towards faults near Mogul and connections with faults in the horsetail splay of the Mt. Rose fault zone.

Two faults are shown on Plate 1 and Figure 33. The longest fault of the two is the northeast one (2.5 km long) that is inferred to go from Alum Creek to Hunter Creek. The fault has an overall strike of N70°W and follows the approximate boundary between hydrothermally altered Kate Peak Formation and unaltered rocks (Thompson and White, 1964). An erosional contrast could be the reason for the step in topography, with the altered rocks to the southwest eroding more easily. Geomorphic features along the fault include linear drainages and swales. This fault is at an elevation of 1890 m (6200 ft) and is probably covered with snow a significant part of the winter. This likely destroys small-scale fault features with processes such as freeze-thaw action. There appear to be a few cross faults that connect this fault and the Crest fault. This inferred fault aligns the southeast with faults mapped by Bonham and Rogers (1983). The other inferred fault is smaller and forms a ramp in the topography and is also continuous with faults to the southeast. The smaller fault has at least one trace that connects with the larger fault. The smaller fault is about 1.25 km long and has an overall strike of N63°W. Because of their proximity to one another and their probable connection, these inferred faults make up one fault zone.

Hines and Ramelli (2016) are mapping a network of faults within the Carson Range and this faulting may continue to the northern front of the range. There definitely appear to be some northwest-striking faults within the range.

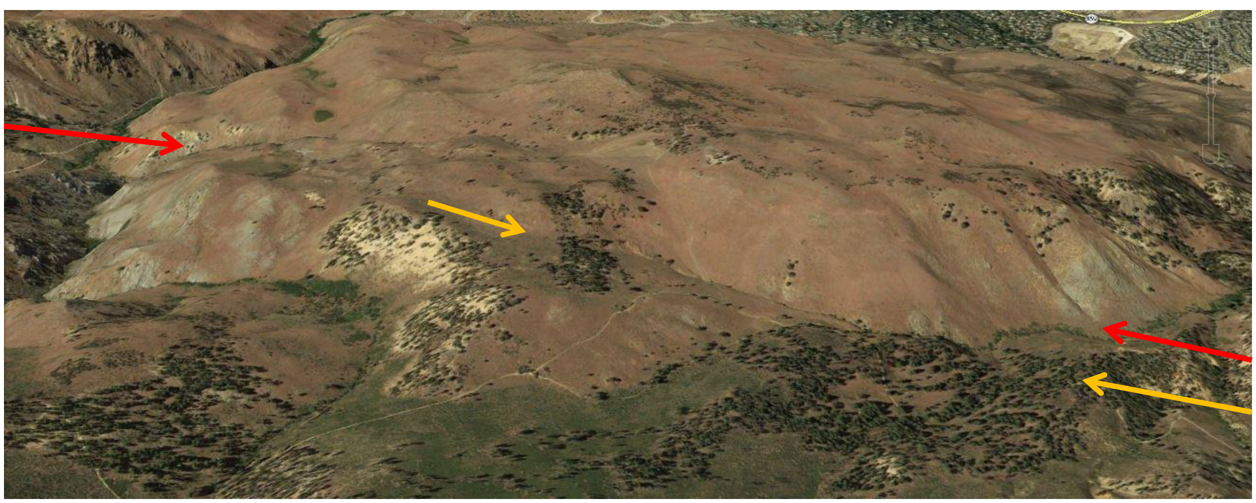


Figure 33. Area of inferred faults, south of the Crest fault in the Caughlin Ranch section. The view is to the north in this Google Earth image. Alum Creek enters on the right and Hunter Creek is on the left. The Crest fault crosses this part of the range at the top of the image. The longer inferred fault goes over the hill between the red arrows and the smaller fault is between the two orange arrows.

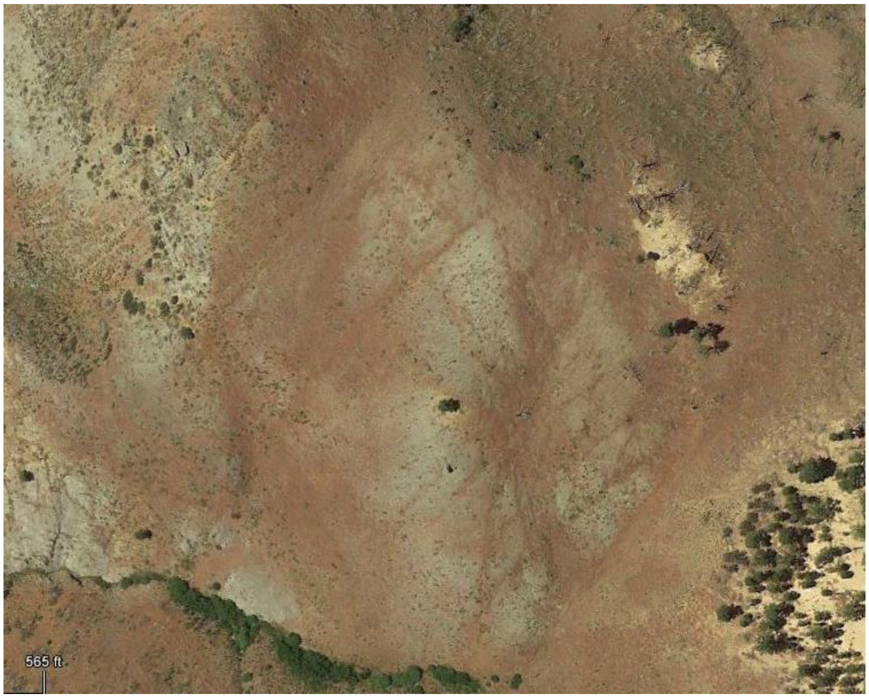


Figure 34. Visible fracture patterns in the vicinity of the southern inferred fault traces indicate that some tectonism is occurring in this area and it is not solely differential erosion. Image from Google Earth

Secondary Faults

Several other smaller faults appear to offset the northern flank of the Carson Range. These faults tend to lie between the larger faults and occasionally connect the two. Faults between the Caughlin Ranch and Crest faults are visible on the LiDAR imagery of the range front (fig.22). These secondary faults include ENE striking normal faults, such as the one that is close to the western end of the Caughlin fault and some are related to the “collapsing” range front. More detailed work on these faults may reveal whether they are part of a wrenching pattern that might be consistent with a right lateral component. Other faults are anticipated to be found with the new, more complete LiDAR. One northwest striking lineament was mapped that is crossing the hillslope at an angle between the Crest and Caughlin Ranch faults (fig, 22).

There are also numerous faults just outboard of the range front that may also be a part of the Washoe Shear Zone (dePolo and others, 2015; Briggs and others, 2015). These are manifested as fault scarps or other topographic alignments. Figure 35 is from Briggs et al. (2015) and shows some of the potential fault traces north of the range front that could be part of the Washoe shear zone.

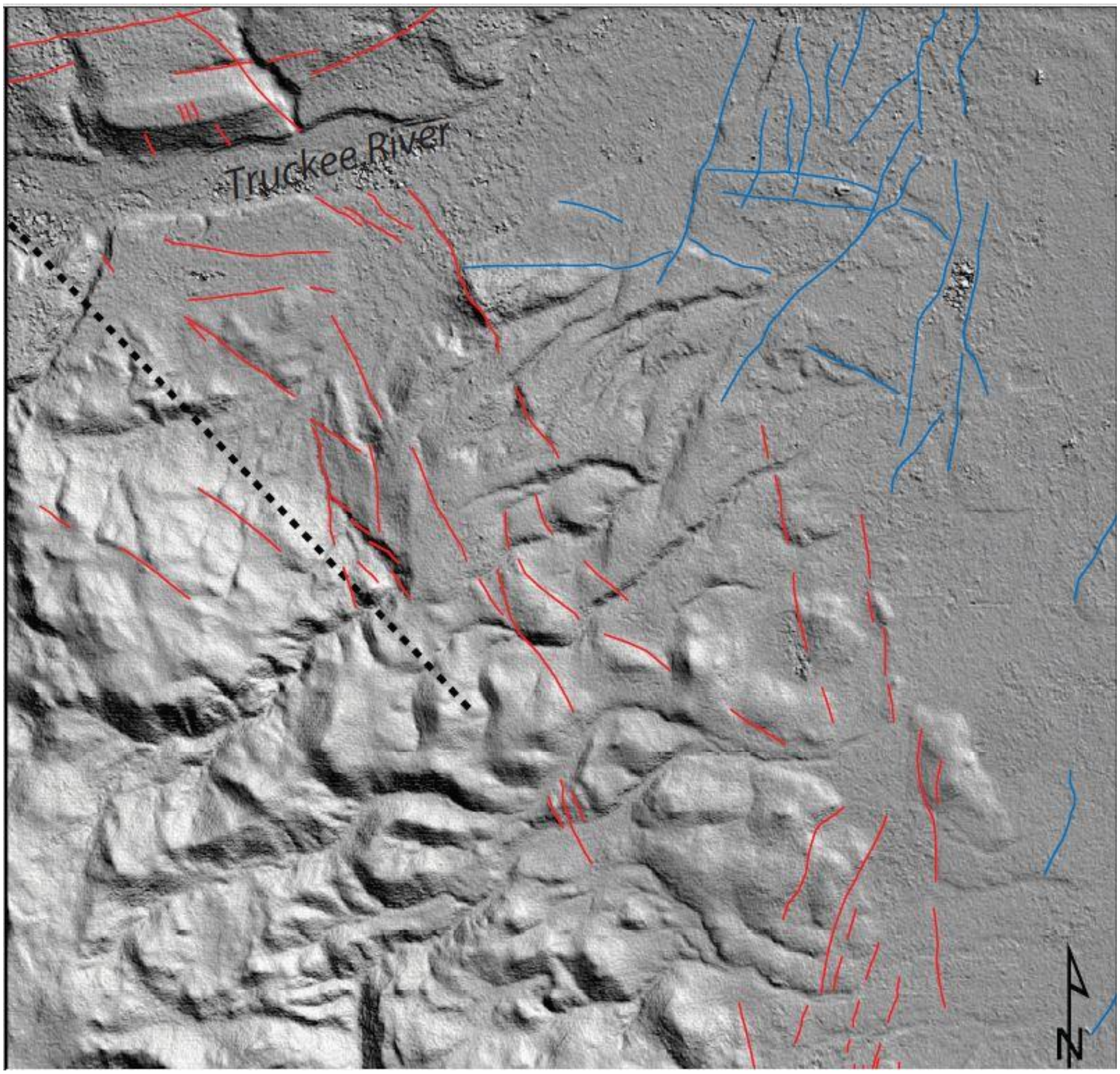


Figure 35. Figure from Briggs et al. (2015) showing potential fault traces that are northeast of the range front and may be part of the Washoe shear zone (red fault traces). Also shown is the 2008 geodetic lineament (small dashes) mapped by Bell et al. (2012).

Inferred Faults West of Hunter Creek

West of Hunter Creek, the softer Hunter Creek Sandstone has been uplifted into the range front and geomorphic features are much more subtle. Nevertheless, potential northwestern extensions of the Crest fault and the inferred fault southwest of the Crest fault are inferred west of Hunter Creek. These inferred northwestward extensions have potential connections with the Mogul fault and possibly the Lawton fault. The northwestern end also may step left to the River Bend fault.

The strongest expressed of the inferred faults west of Hunter Creek, is the southwestern trace (Plate 3, fig. 36). The fault crosses Hunter Creek where two branches of the creek come together and crosses up the western canyon wall. From there it is mapped down a couple gullies and runs along the base of a west-facing hill along a fault mapped by Thompson and White (1964). At the westernmost end, there is a small left step to the Mogul fault. This inferred fault is 3.5 km long and has a general strike of N38°W.

The inferred northwestward extension of the Crest fault crosses Hunter Creek after a small right step. It is mapped along some weak topographic lineaments and springs. This inferred fault is about 3 km long and strikes N40°W. A second, less certain, splay of this fault is inferred just to the north of this second fault at Hunter Creek. This trace is inferred down a wash and towards the Lawton fault.

The softer sandstone and other sediments being uplifted into the range front is a rather dramatic example of how the uplift postdates The Hunter Creek Sandstone (fig. 36). Henry and Perkins (2001) posit that these Tertiary sediments covered much of the northern Carson Range prior to uplift, and that these sediments have since been stripped during the Quaternary. An alternative explanation for the geomorphology that was mapped as faults would be differential or preferential erosion within these softer sediments. Further work needs to be conducted to confirm or refute these inferred fault traces.

2008 Geodetic Lineament

The 2008 geodetic gradient lineament of Bell et al. (2011) passes roughly along the base of the range front, below the identified faults within the range. There aren't many small-scale geomorphic features at the surface that support a fault in this position. The base of the range is very steep and there may be at least one block calving off below the bench in the range that could be related to a normal fault. There is also an inflection in the lower slope with a spring line that could be a fault (fig. 37) but this is close to some geologic contacts and could be differential erosion as well. A few minor faults have been found in Tertiary deposits around the base of the range. Given the sum of the features, especially the steep range front, it seems possible that there is a blind fault along the base of the range front.

The geodetic lineament has several implications. First a magnitude 4.9 earthquake like Mogul can occur along it, because it did in 2008. On the other hand, the southeastern half of the lineament had no earthquakes along it in 2008, so it demonstrates that aseismic deformation occurs along the Washoe shear zone as well. To Bell et al. (2012), the lineament was support for an incipient lateral fault zone in the area.

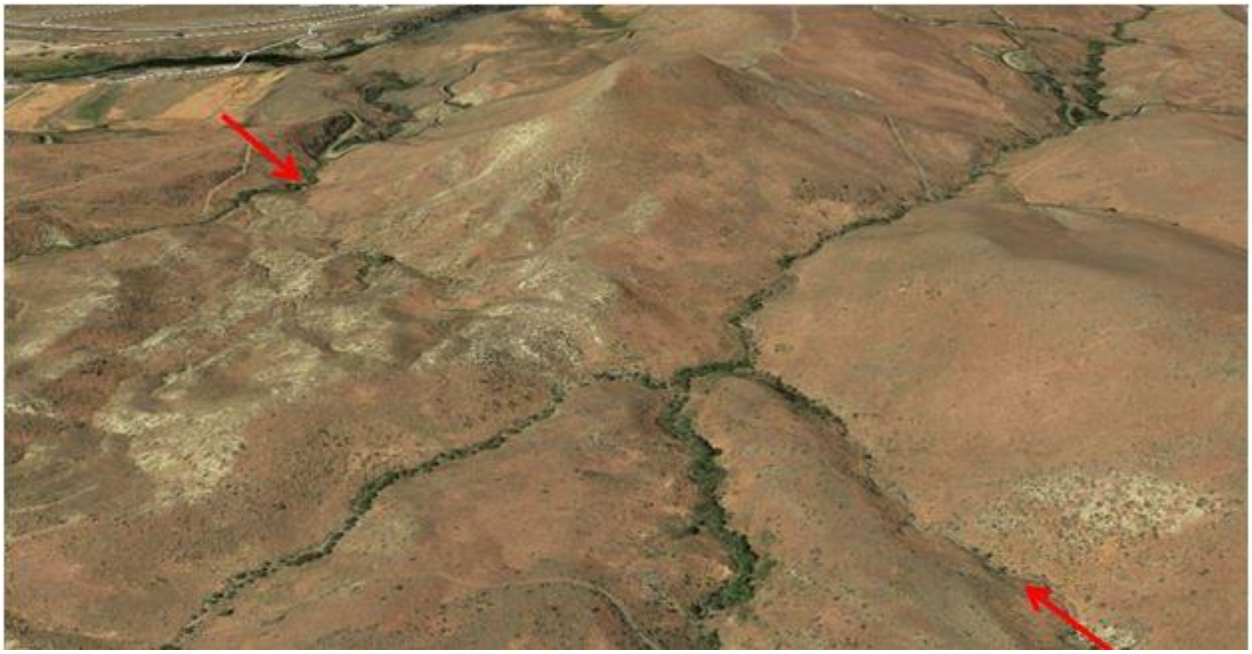


Figure 36. Southwestern inferred fault west of Hunter Creek. The fault was inferred between the two red arrows and some topographic lineaments can he seen in the certer of the Google Earth image. View to the north-northwest.

Figure 37. Scarp (red arrow) along the base of the Carson Range front that is in the vicinity of where the 2008 geodetic lineament was mapped. View west on a Google Earth image.

Mogul-Verdi Section

The Mogul-Verdi section of the Washoe shear zone is a complicated, but highly informative geologic setting that has been mapped and studied well (c.f. Bell and Garside, 1987; Trexler et al., 2012; Cashman et al., 2012). Knowing the existing fault structure had limited value in identifying the fault that the 2008 Mogul earthquake occurred along, as it was a blind event that did not follow a mapped fault nor rupture the surface. Overall, late Quaternary faults are difficult to identify and define in this section. Only some areas have Quaternary alluvium (Bell and Garside, 1987; Ramelli et al., 2011) and geomorphic features appear to be poorly preserved in the Hunter Creek Sandstone, the most common geologic unit present.

Figure 38. Google Earth oblique image. Remnants of the Tertiary basin are in the central part of the image between the Carson Range (bottom) and Peavine Mountain (top). The Washoe shear zone crosses the image from the lower right, through the center, and towards the upper left, with a possible continuation into California.

The Mogul-Verdi section of the Washoe shear zone disrupts a Neogene basin that opens eastward into the Reno basin and includes the Verdi basin to the west. In the Miocene, this was a part of a much larger basin that extended well beyond the Verdi area (Henry and Perkins, 2001). The local part of the basin that is preserved is in a low area between the relative uplift of the Carson Range and Peavine Mountain. The Tertiary basin was filled with volcanic flows and sediments from late Miocene to earliest Quaternary (10 to 2.6 Ma; Henry and Perkins, 2001; Trexler et al., 2012; know locally as the Hunter Creek Sandstone). Following this period of sedimentation, granitic and glacially polished rocks of the "Gravel of Reno" were laid down and faulting of the basin in the Verdi and Mogul areas was initiated (Henry and Perkins, 2001;

Trexler et al., 2012). Post-basin, Quaternary tectonism broke up this basin and the Washoe shear zone separated the Verdi and Reno basins The larger basin was also disrupted by 2 km of normal dip-slip offset by the Verdi fault (Henry and Perkins, 2001). Disruption of this basin started between 3.1 and 2.6 Ma (Henry and Perkins, 2001; Trexler et al. 2012)). This time period was also the beginning of local tectonism and uplift in the Carson Range. This tectonic activity caused general eastward tilting of the Tertiary and Quaternary sediments in the central part of the western Reno basin. Tertiary deposits adjacent to the mountains are tilted towards the basin, commensurate with the uplift of the mountains. For example, Hunter Creek Sandstone sediments on the northern side of the Carson Range are tilted to the north. Dips of the sediments within the basin are commonly between 15° and 35°, and can be steeper along the flanks of the mountains and where the Washoe shear zone crosses the basin. Additionally, where the Washoe shear zone crosses the basin, dips are less uniform and are in many different orientations.

Faults within the disrupted basin bound and offset Cretaceous granodiorite; late Miocene basaltic andesite, andesite, and dacite lava flows; late Miocene conglomerates and sandstones; and late Miocene diatomaceous siltstones and sandstones. As portrayed by Bell and Garside (1987), Ramelli et al. (2011), and Trexler et al. (2012), the faults strike northwest, north, and northeast, and form a rhombic pattern just north of Mogul. The faults are commonly straight. They intersect each other with terminations and offsets. The main faults portrayed in Trexler et al. (2012) and Cashman et al. (2012) in the Mogul area are two north-south striking faults, the Mogul and the Lawton faults (figs. 39 and 40). The 2008 Mogul earthquake was effectively a blind secondary fault that was between the Mogul and Lawton faults and had a more northwesterly strike (fig. 42).

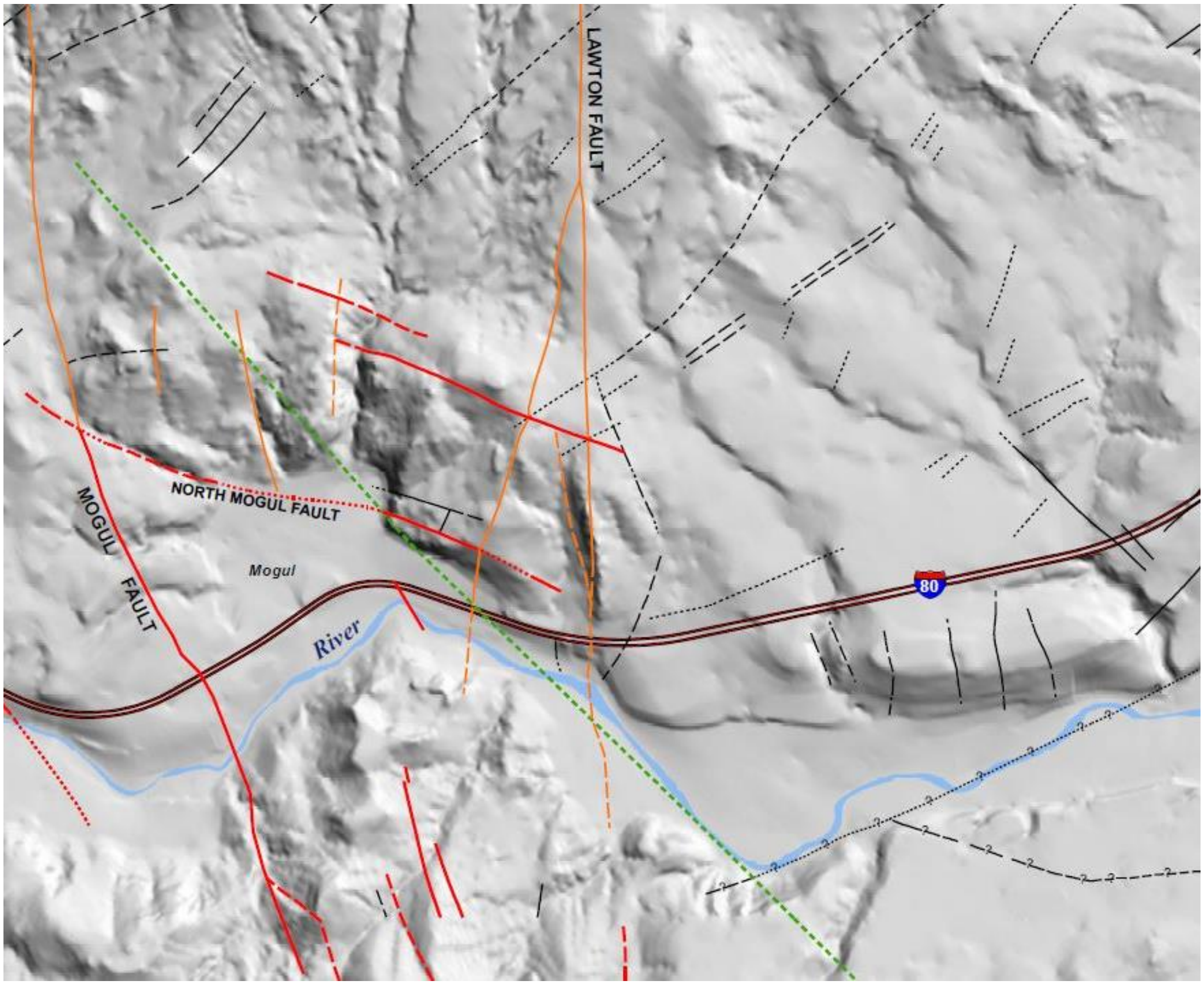


Figure 39. Section of Plate 3 showing the Mogul area and local faults.

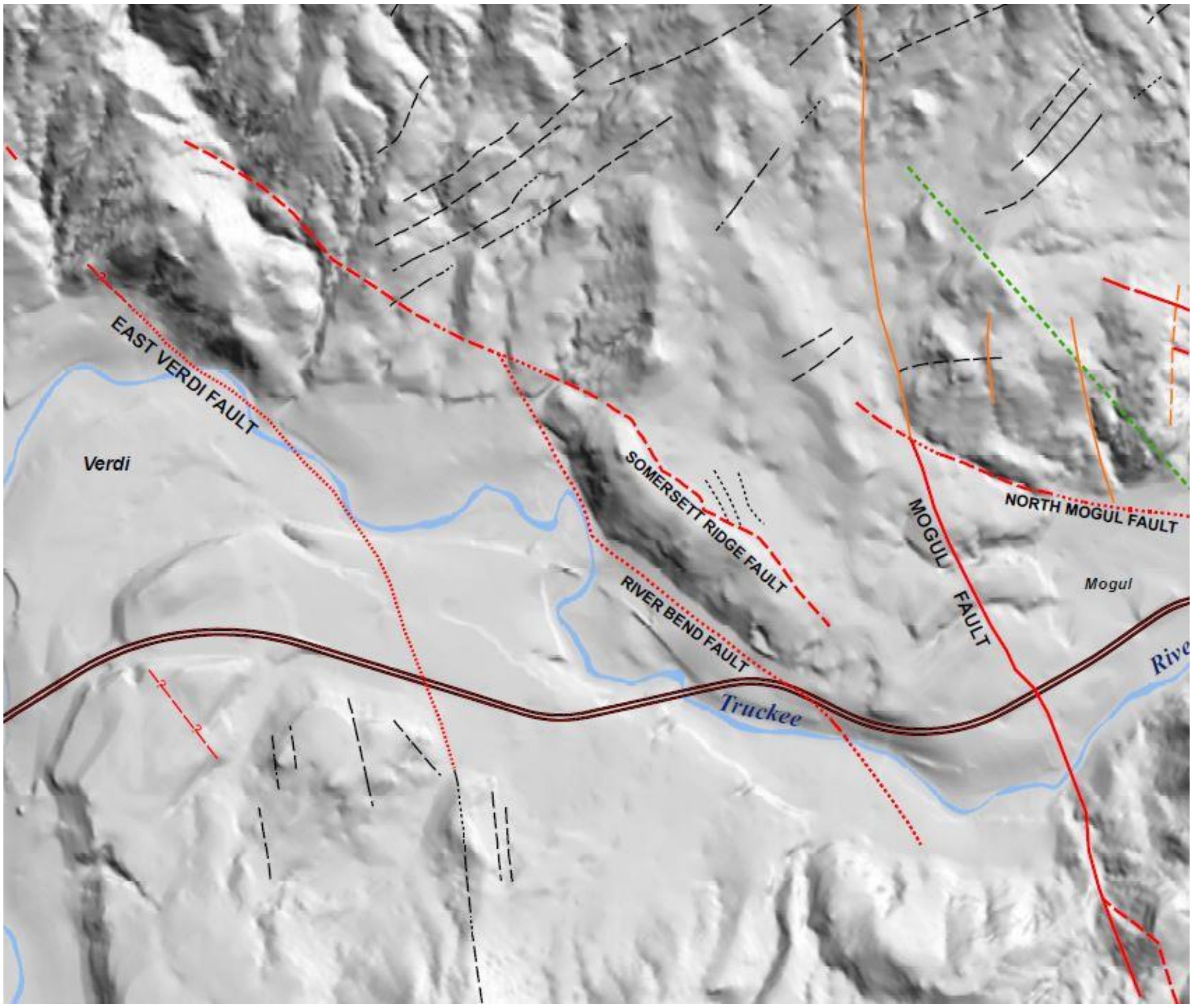


Figure 40. Section of Plate 3 showing the Verdi area and local faults.

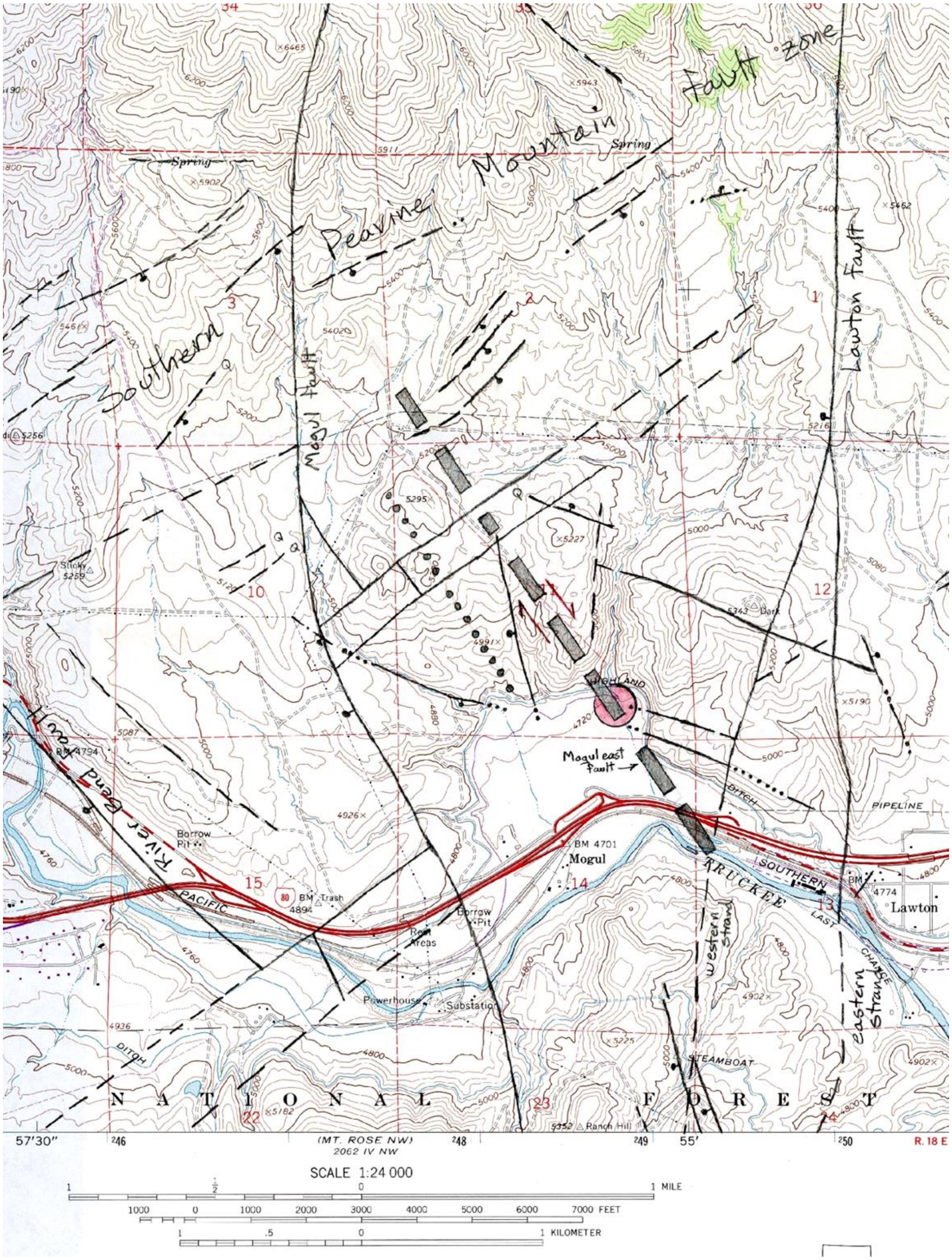


Figure 41. Sketch fault map made for the 2008 Mogul earthquake. Compiles faults mapped by Bell and Garside (1987) and Trexler and Cashman (2008, unpublished research). Figure is from dePolo (2011). The red dot is the 2008 mainshock epicenter and the wide dashed line is the approximate rupture surface.

Surficial faults in the Mogul area formed during the Quaternary (Henry and Perkins, 2001; Trexler et al., 2012; Cashman et al., 2012). Cashman et al. (2012) measured three sets of faults that formed during this time period, including north- and northwest-striking right-lateral strike-slip faults with subhorizontal slip indicators that formed contemporaneously with a conjugate set of left-lateral faults. Cashman et al. (2012) note that steeper, younger new strike-slip faults were formed as the older faults were rotated by the tilting and their dips began to shallow. Cashman et al. (2012) comment that the best preserved large offsets along the right-lateral faults “required 10s if not 100s of meters of dextral slip to create 12 m of stratigraphic offset.” These observations support the existence of strike-slip faults and indicate that they began forming early in the local disruption of the Tertiary basin.

Although significant right-lateral strike-slip faulting has been clearly documented in the Mogul area, Cashman et al. (2012) state that the general mapped pattern of the east-west basin does not lend itself to large amounts of lateral offsets (i.e., the relict basin itself does not appear to be laterally offset).

Geophysical anomalies that support the Washoe shear zone in the Mogul-Verdi area include the 2008 InSAR gradation lineament (Bell et al., 2012), linear, northwest-trending Bouguer gravity anomalies (Cashman et al., 2012), the northwest-trending aftershock zone associated with the Mogul earthquake, and the 2008 mainshock rupture..

Potential Late Quaternary Faults

Faults in the Mogul-Verdi section have been mapped by Bell and Garside (1987), Henry and Perkins (2001), Trexler et al. (2012), Ramelli et al. (2011), and Cashman et al, (2012), and are compiled and slightly modified in Figures 39 and 40. Two of the longer faults in the area that are mapped by Trexler et al. (2012) are the north and northerly striking Mogul fault (strike: N3-25°W; length: ~5.5 km) and Lawton fault (strike: N1°W; length ~5.5 km).

Some of the most prominent northwest-striking faults in the Mogul-Verdi section are between Mogul and Verdi. These faults are generally on trend with faults in the Northern Carson Range section. At the Truckee River, the southern northwest-striking part of the Mogul fault is aligned with inferred faults in the Caughlin Ranch reach and is in a favorable orientation for a lateral component. There is a ~1 km left step between this and the River Bend fault (strike: ~N52°W; length: ~3.5 km; shown as having right-normal-oblique displacement on Ramelli et al., 2011, cross section B-B’). In this area is a 2-km-long northwest-trending ridge (Somersett Ridge) that has the Truckee River flowing along the west side and crossing its southern end. This ridge is a horst, with the River Bend fault bounding the west side (defined by gravity; Ramelli et al., 2011.) and the herein named Somersett Ridge fault on the east side (strike: ~N47°W; length: ~3.5 km; shown as a normal fault on Ramelli et al., 2011 cross section B-B’). This ridge has a complete set of river terraces on its southern end, which may be well preserved partly because of relative uplift during tectonic events or episodes. On the north side of the ridge, the Somersett Ridge fault bends more westerly, truncates the River Bend fault, and continues in a northwest direction up the southwestern flank of Peavine Mountain (slightly modified from Ramelli et al., 2011). There is another ~1 km left step to the herein named East Verdi fault (strike: N8-47°W; length:~5.5 km). Similar to the River Bend fault the East Verdi fault is largely concealed by the Truckee River and its flood plains. An exception is at the northern end of the fault where it appears to climb up the flank of the mountainside and may extend to the northwest into California.

Several other smaller faults have been mapped or inferred between the larger faults, and some of these have northwest strikes. One of these faults may have some possible geomorphic evidence of late Quaternary activity, the North Mogul fault (strike: ~N67°W; length: 3 km). Another inferred and questioned northwest-striking fault is just west of the East Verdi fault and is mapped by Bell and Garside (1987); Ramelli et al. (2011) show this fault as having a right-lateral component of displacement on their cross-section B-B'.

Tectonic geomorphology along the faults in this section is rare. The setting is dominantly erosional and the dominant rock type is the softer Hunter Creek Sandstone. The geomorphic setting is dominated by erosion and down cutting by the Truckee River. This has left a suite of terraces along the river. Additionally, there are pediments adjacent to the range fronts and tectonically formed hills within the basin. Tectonism along the Washoe shear zone has created an overall northwest trending upland in the Mogul area. This upland area has been eroded by smaller drainages, many of which are following faults. Active deposition only occurs in flood plains along the Truckee River and in a few small patches of alluvial pediments and fans (Mock, 1972; Ramelli et al., 2011). A few alluvial fault scarps have been recognized in the area. There were three short parallel fault scarps along the Southern Peavine Mountain fault zone that are adjacent to the surficial projection and northern end of the 2008 M4.9 Mogul earthquake (Bell and Garside, 1987). A couple fault scarps were mapped just east of Chalk Bluffs and a couple late Quaternary pediments had visible faults in them (Mock, 1972). On the eastern side of Mogul, the North Mogul fault has a swale up a hillside that may be related to surface offset. Immediately northwest of Mogul there is a subtle trough a few meters long preserved along a fault that may be from a paleoearthquake. Although this has been mapped as the North Mogul fault, this may be a separate fault as this section of the North Mogul fault is going to be remapped to the north (James Faulds, 2017, pers. comm.). Overall, most of the northwest-striking faults are in an eroding landscape and/or are covered by the Truckee River.

The Truckee River has gradually eroded down through the basin and upland, and has three right jogs in it where the shear zone crosses it. These jogs are likely the result of fault-controlled erosion and possibly some offset. Fault-controlled erosion was confirmed in the large apparent right step in the river trend just southeast of Mogul. Along this reach of the Truckee River, its location is controlled by a significant fault zone that was viewed in an excavation for a water pipeline crossing (dePolo, 2010, unpublished research; fig. 39).

Faults that are mapped in this section offer a unique view of the faults that have been involved in the Washoe shear zone activity during the late Neogene. This is because Tertiary sediments and volcanic rocks cover older faults that have not been involved with the shear zone. This is unlike the bedrock areas of the Carson Range where all the faults, including pre-shear zone faults, are exposed or the Quaternary pediment areas where only the most recent and most active Quaternary faults of the shear zone are evident.

A series of alluvial terraces have developed along the Truckee River as it eroded into basin sediments in response to local uplift, coupled with changes in river flow from upstream glaciations. There is evidence for nine Quaternary river terrace levels that have been identified and mapped by Mock (1972), Bell and Garside (1987), and Ramelli et al. (2011). Terrace profiles were constructed by Mock (1972) and these were examined for any deformation. The river and terraces follow northwest-striking faults just east of Verdi. Southeast of where the River Bend fault crosses the river, the terraces are at a moderate angle with faults.. In this area, one possible event signal is just west of Mogul where terraces IV and V have steeper eastward gradients than younger terraces over about a kilometer distance (fig. 42). This needs to be examined in detail, but if this slope difference was caused by an earthquake, then the event was between the ages of terraces IV and III, or in the late Quaternary (Mock, 1972; Ramelli et al., 2011). Additionally, the one place where all the terraces are preserved is the southern nose of Somersett Ridge (Mock, 1972; Bell and Garside, 1987). These may be more completely preserved there because relative tectonic uplift of the ridge helped isolate some of the terraces. The terraces are worth studying further.

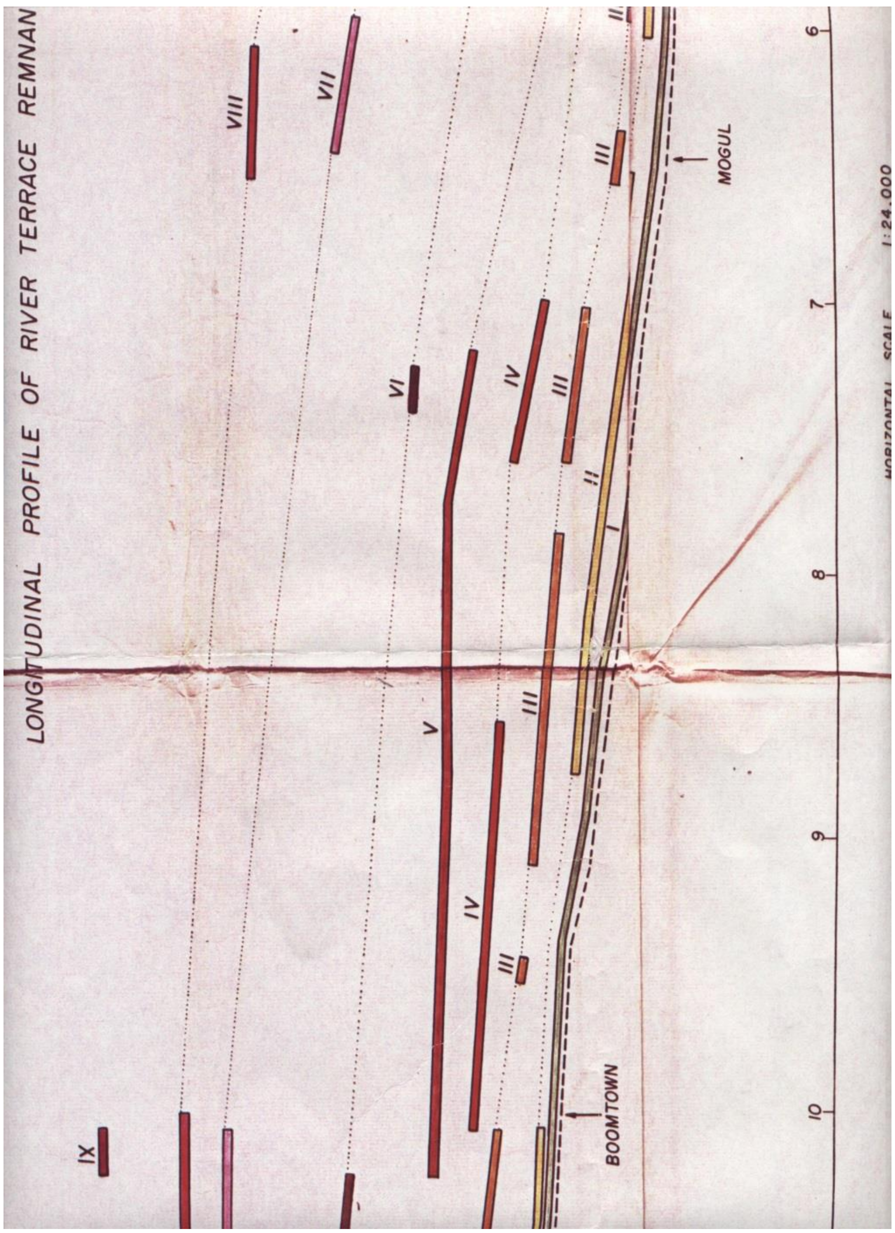


Figure 42. Section of Plate 2 from Mock (1972) that shows terrace profiles longitudinally along the Truckee River. The section shown is just west of Mogul, near Somersett Ridge. Lower scale is in miles.

Possible

Southern Extension of the Washoe Shear Zone

The Washoe shear zone is partly defined by semi-anomalous northwest-striking faults in a region where northerly or northeasterly striking faults are more common. During this study it was discovered that there are northwest-striking faults farther south of Steamboat Hills (Plate 1). This idea was also prodded by one of the scientists who mapped the geology of the Virginia City Quadrangle, Don Hudson; he noted possible right-lateral offsets on one of the main faults mapped in the geology of the Virginia City Quadrangle. A few geomorphic anomalies indicate the potential for late Quaternary activity along this southern projection, but this was not studied further. The southern zone could extend as far south has Mound House, includes a buried fault in Washoe Valley that bounds the western side of the Virginia Range (Ramelli et al., 2011), and poses an additional potential hazard to Carson City. It would also be responsible for uplifted bedrock within a topographic low called the Carson lineament.

EARTHQUAKE ACTIVITY ALONG THE WASHOE SHEAR ZONE

Western Nevada has a high level of background earthquake activity and has a seismic network that covers the area of the Washoe shear zone. For an excellent summary of local seismicity, see Ruhl et al. (2016). A few earthquakes have occurred in the shear zone during this study and focal mechanisms for these events were made by the Nevada Seismological Laboratory in their moment tensor studies and for a few smaller events, by Diane dePolo. These events were plotted by Briggs et al. (2015) and are shown in Figure 43. The few focal mechanisms were consistent with a lateral component and had a nodal plane that was parallel to faults in the Washoe shear zone. The same is true for the 2008 Mogul earthquake focal mechanism only the aftershock pattern confirms it was the northwest plane that was active.

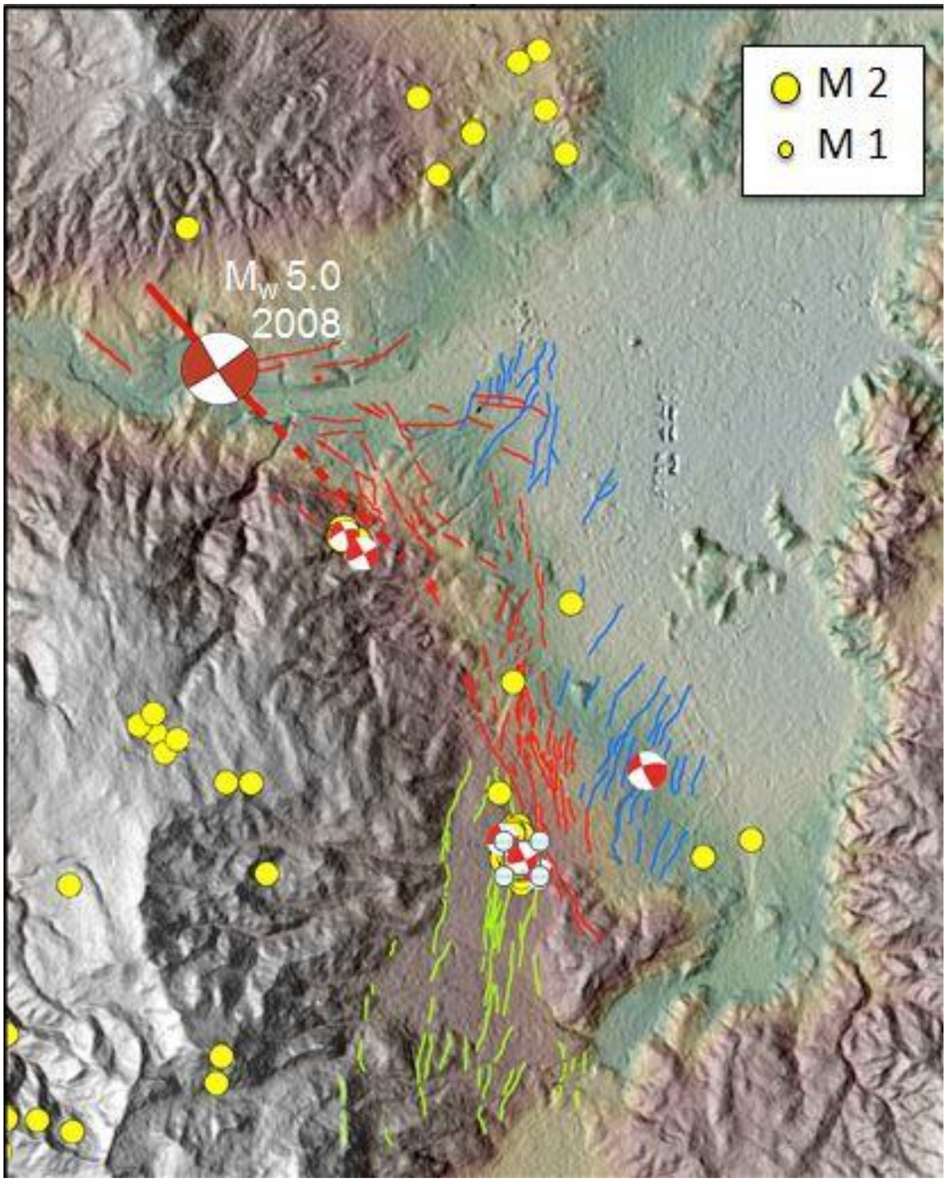


Figure 43. The 2008 Mogul earthquake focal mechanism and some seismicity that occurred during the study near the Washoe shear zone. Focal mechanisms are from the Nevada Seismological Laboratory. The figure is from Briggs et al. (2015) and portrays the shear zone as red faults. The focal mechanisms are strike slip in nature and have a nodal plane that is parallel to the shear zone.

Ruhl et al. (2016) found a little over 70% of the earthquakes they examined in the Reno-Lake Tahoe region had strike-slip focal mechanisms. In the area of the Washoe shear zone most mechanisms were strike-slip, but there seemed to be a higher percentage of normal and oblique mechanisms (fig. 44), The oblique mechanisms were both normal and reverse. A reverse-oblique mechanism is significant in the Basin and Range Province as such events are more likely in areas with a lateral component and fault complexities versus pure extensional areas.

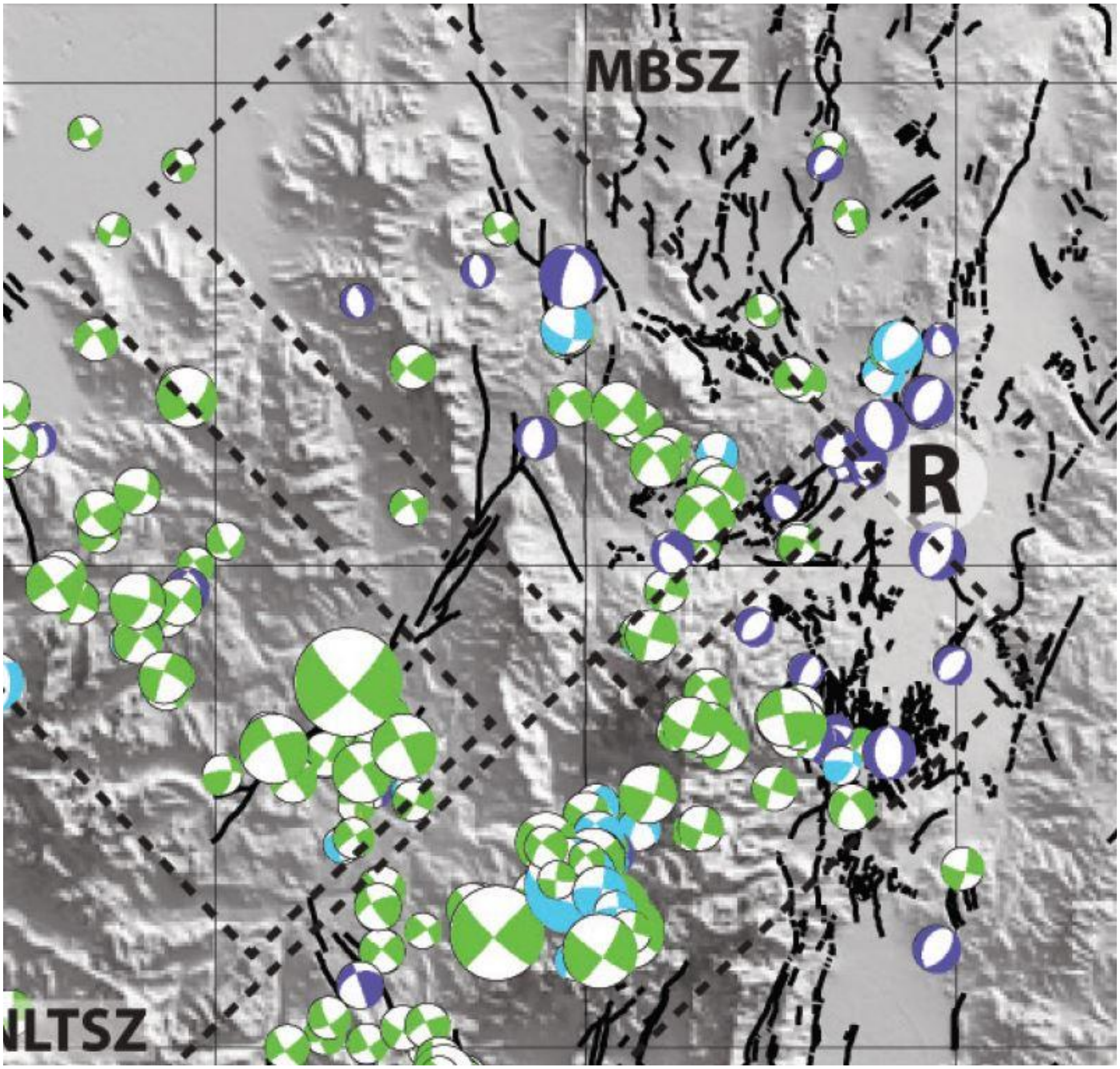


Figure 44 Part of Figure 4a from Ruhl et al. (2016) that shows focal mechanisms in the Washoe shear zone region. Green mechanisms are strike-slip, purple mechanisms are normal dip-slip, and blue mechanisms are oblique slip. Note the dominance of strike-slip focal mechanisms and the northwest nodal planes that are parallel to faults in the shear zone. "R" is where Reno is and the Washoe shear zone is in the right-central part of the figure.

Ruhl et al. (2016) also deduced the local stress regime in their earthquake analysis. Their results are consistent with a right-lateral component along northwest-striking faults and changes in the stress regime correspond to changes in the overall strike of the Washoe shear zone. Ruhl et al. (2016) determined the overall T-axis direction (horizontal extension direction) in the Reno-Carson City urban corridor was well resolved at N69.0°W ±12.9°. This is consistent with having a right-lateral component on the Mt.

Rose Pediment section and the possible southern extension (overall strikes N30-35°W). The Carson Range and Mogul-Verdi sections have a more westerly overall strike (~N50°W). Ruhl et al. (2016) found that T-axes directions are rotating across the Nevada-California state line from west-northwest to east-northeast. This is consistent with a more westerly striking northern part of the Washoe shear zone; if this consistency is demonstrated further this would indicate that this local stress regime rotation is a long term phenomena, not just decadal.

Lastly, Ruhl et al. (2016) suggest that the 1948 Verdi earthquake (M6) was in their Mogul-Bordertown source zone. This is an intriguing idea and if true would mean this earthquake likely occurred along the northern part of the Washoe shear zone. Other local earthquakes, such as the 1914 Reno earthquakes (M6 and M6.4), have unknown epicenters, and there is always an outside chance that features such as the young break along the Caughlin Ranch fault or other features, could be related to events like these.

Two seismicity maps were constructed for this study, one with seismicity from 1857 to 2015 (fig. 45) and one with the faults from Plate 1 to compare with the earthquakes (fig. 46). The earthquake data base was made up of a historical catalog put together by myself that goes up through 1969 and the Nevada Seismological Laboratories earthquake catalog for earthquakes from 1970 through 2015. Background seismicity occurs in the Mogul area, the Mt. Rose pediment, and the adjacent Carson Range front. One location that is seismically active is the intersection of the Mt. Rose Pediment fault zone and the Arrowcreek fault. There is also seismic activity within the eastern Carson Range near the intersection of the western fault of the Mt. Rose fault zone horsetail splay and the Evans Creek Headwaters fault zone.

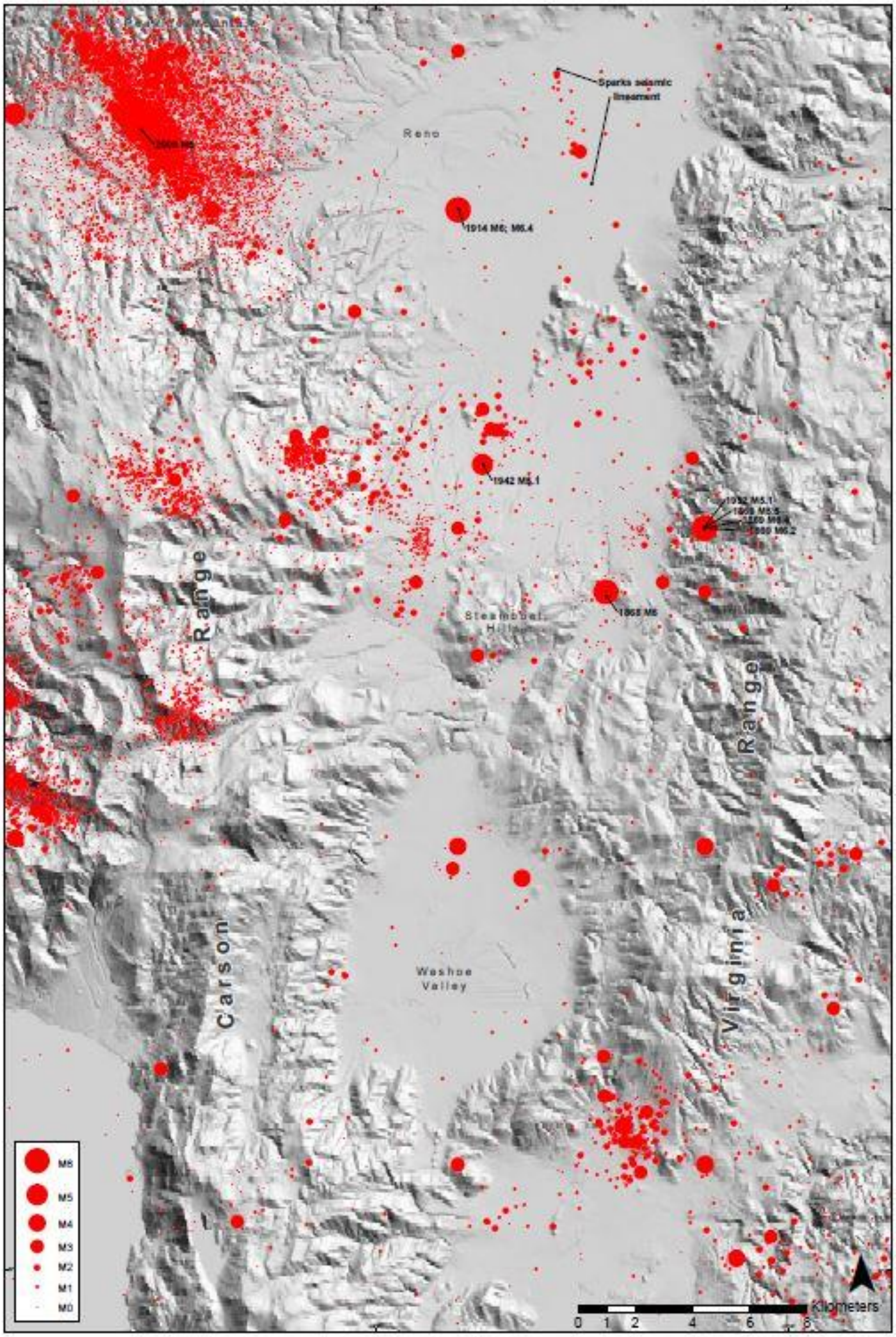


Figure 45. Seismicity in the Washoe shear zone area from 1857 to 2015. Earthquakes are from my unpublished catalog of historical earthquakes and the Nevada Seismological Laboratory earthquake catalog.

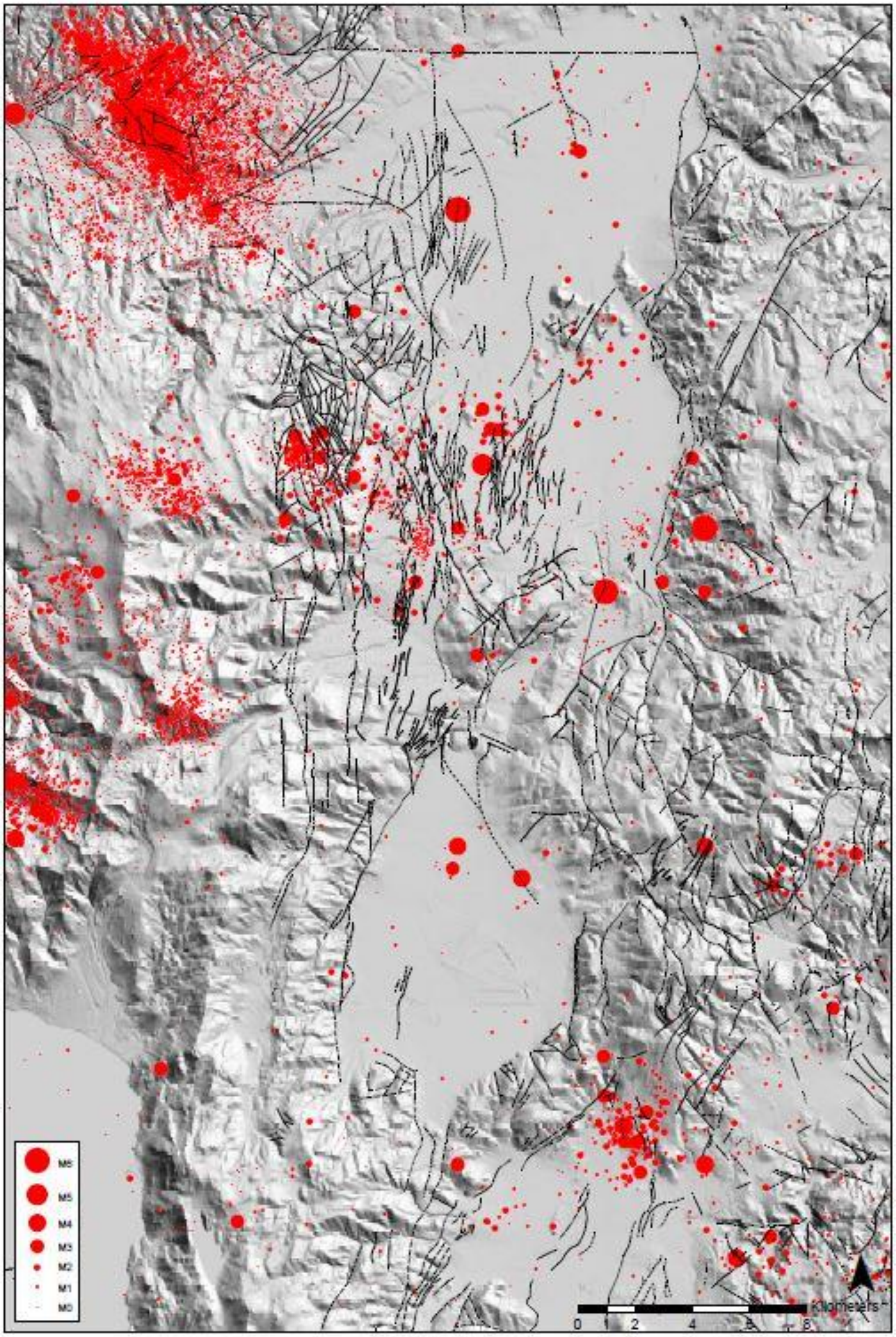


Figure 46. Seismicity from Figure 45 and the faults from Plate 1 to show any potential relationships between the earthquakes and faults.

POTENTIAL SEISMIC HAZARD

Because of the reconnaissance nature of this study, no detailed earthquake analysis was conducted - there is still too much uncertainty in the extent, the specific components, and the behavior of the Washoe shear zone. Although fault lengths can be correlated with magnitudes using Wesnousky (2008), there was little earthquake occurrence information and it was highly incomplete and uncertain. Many of the faults in the northern half of the shear zone are short, but align with one another. Even with the distributed and discontinuous nature of the shear zone, there is enough continuity and overlap of faults that a failure of the entire northern half of the zone as a single 28-km-long source, cannot be ruled out. The entire zone as known today is 48 km long. The faults identified in this study, their lengths, and correlated moment magnitudes are given in Table 3. Estimated potential magnitudes of individual faults are from M5.6 to M6.1. If the northern half of the Washoe shear zone failed as an earthquake it would correlate with a magnitude 6.7 event, and if the entire current extent of the shear zone failed, it would correlate with a magnitude 7.0 event. There are also several connections between faults within the Washoe shear zone and other adjacent faults, such as the Mt. Rose fault zone. An earthquake rupture on an adjacent fault could trigger slip on faults within the Washoe shear zone. A historical event that could be an analog to an earthquake that fails the entire shear zone would be the 1932 Cedar Mountain earthquake, a right-lateral strike-slip event with a moment magnitude of 7.1. Surface breaks over the top of this earthquake were strike-slip and normal.

Detailed fault slip rates were not determined in this study and will take quite a bit of effort to obtain, but I would consider this the next critical step in research on the Washoe shear zone. A complexity in this effort will be the zone like nature of the shear zone and understanding the behavior of faults within a particular section. Detailed studies will be needed to work around uncertainties and alternative hypotheses. For example, stream channel offsets were measured by Briggs et al. (2015) in the Mt. Rose Pediment section. How much of the offset was due to juxtaposition because of the normal component or erosion versus the tectonic offset was difficult to document. Estimates based on the data in Briggs et al. (2015) yield right-lateral strike-slip rates of 0.1 to 1 m/ky. Compared to the geomorphology of other strike-slip faults in Nevada, this range is about correct. The higher value would likely be cumulative across multiple faults. Limited trenching studies might favor the slower rate, but these studies have been along the smaller faults in the zone. A couple of earthquakes since the Sangamonian period, ~80 ka, would be consistent with these initial results. If offsets were 2 m each time, that would be a slip rate of 0.05 m/ky, and recurrence rates would be tens of 1000s of years, for a single fault (two such faults could be 0.1 m/ky). Larger fault scarps with more complete paleoearthquake histories need to be trenched to gain a more complete understanding of the activity of the Washoe shear zone. At this point, an estimate of 0.1 to 1 m/ky for the right-lateral component is reasonable.

Table 3. Potential Late Quaternary Faults that may be Members of the (northern?) Washoe Shear Zone

Fault Name	Length	Estimated Sense-of-Slip	Most Recent Activity	Potential Earthquake Magnitude[1]
Mt. Rose Pediment fault zone	10	Right-normal oblique slip	Holocene?	6.3
Arrowcreek fault	3	Right-lateral?	Holocene?	5.8
Angela's fault zone	6	Right-normal oblique slip	late Pleistocene?	6.1
Evans Creek Headwaters fault zone	5-5.5	Right-normal oblique slip	late Pleistocene?	6.0-6.1
Caughlin Ranch fault zone	1.8-2	Normal right-lateral strike-slip?	late Pleistocene?	5.6
Crest fault	2.2-4.3	Right-normal oblique slip?	late Pleistocene?	5.6-5.9
Inferred fault in southwest	2.5			5.7
Lawton fault	5.5	Right-normal oblique slip	Quaternary	6.1
Mogul fault	5.5	Right-normal oblique slip	Quaternary	6.1
North Mogul fault	3	Normal right-lateral strike-slip?	late Pleistocene?	5.8
Somersett Ridge fault	3.5	Right-normal oblique slip	late Pleistocene	5.9
River Bend fault	3.5	Right-normal oblique slip	Quaternary	5.9
East Verdi fault	5.5	Right-normal oblique slip	Quaternary	6.1
N. half Washoe shear zone	28			6.7
Entire Washoe shear zone	48			7.0

1 = **Wesnousky (2008) - All Fault Types, L**ength (L, km):
$M_w = 5.30 + 1.02 \log(L)$

DISCUSSION

This study was more exploratory than judicious. Late Quaternary faults were sought after rather than a focus on critically reviewing the activity of faults. This was because this is a newly discovered shear zone versus work on an identified structure, and an exploratory nature was needed to develop the shear zone. This means some identified structures (fig. 47) may not be late Quaternary faults. Alternatively, poor geomorphic preservation of faults in the mountains likely means some late Quaternary faults have been missed. But this study is a good start to developing the shear zone more definitively. It is worth more effort to characterize the earthquake hazard of the zone. The potential southern half of the Washoe shear zone has not been studied yet and has a more simplistic portrayal in Figure 47 than the north half.

More definitive work is needed on the Washoe shear zone. But at this time there are multiple lines of evidence and a number of reasons to believe that a fault zone with a right-lateral strike-slip component exists; these are listed in Table 4.

Table 4. Factors that Support the Existence of a Washoe Shear Zone that Accommodates a Component of Right-Lateral Strike-Slip Motion.

1) 2008 Right-lateral northwest-striking Mogul, Nevada earthquake (**M**4.9),
2) Zone of northwest-striking faults in a stress regime with an approximately east-west- to west-northwest-directed least-principal horizontal stress direction,
3) Mulitple scales of left-stepping en echelon patterns of faults,
4) Trenches exposing vertical and upwards opening flower structures with limited vertical offset in some cases,
5) Some strike-slip focal mechanisms along the shear zone, nodal planes that are parallel to faults in the zone, in a region that is dominated by strike-slip background earthquakes,
6) Right-lateral deflections of some stream channels,
7) Strike-slip tectonogeomorphology including linear ridges, troughs, stream channels, and spring alignments; back-facing scarps; side-hill benches; and mountain-side benches,
8) Northwest-striking inferred fractures adjacent to the shear zone that produce thermal water at Steamboat Springs,
9) Relatively linear faults
10) Kinematic consistence with other local faults (locations and tectonics),
11) Alignment of late Quaternary tectonic features including volcanoes, basement uplifts, and hot springs.

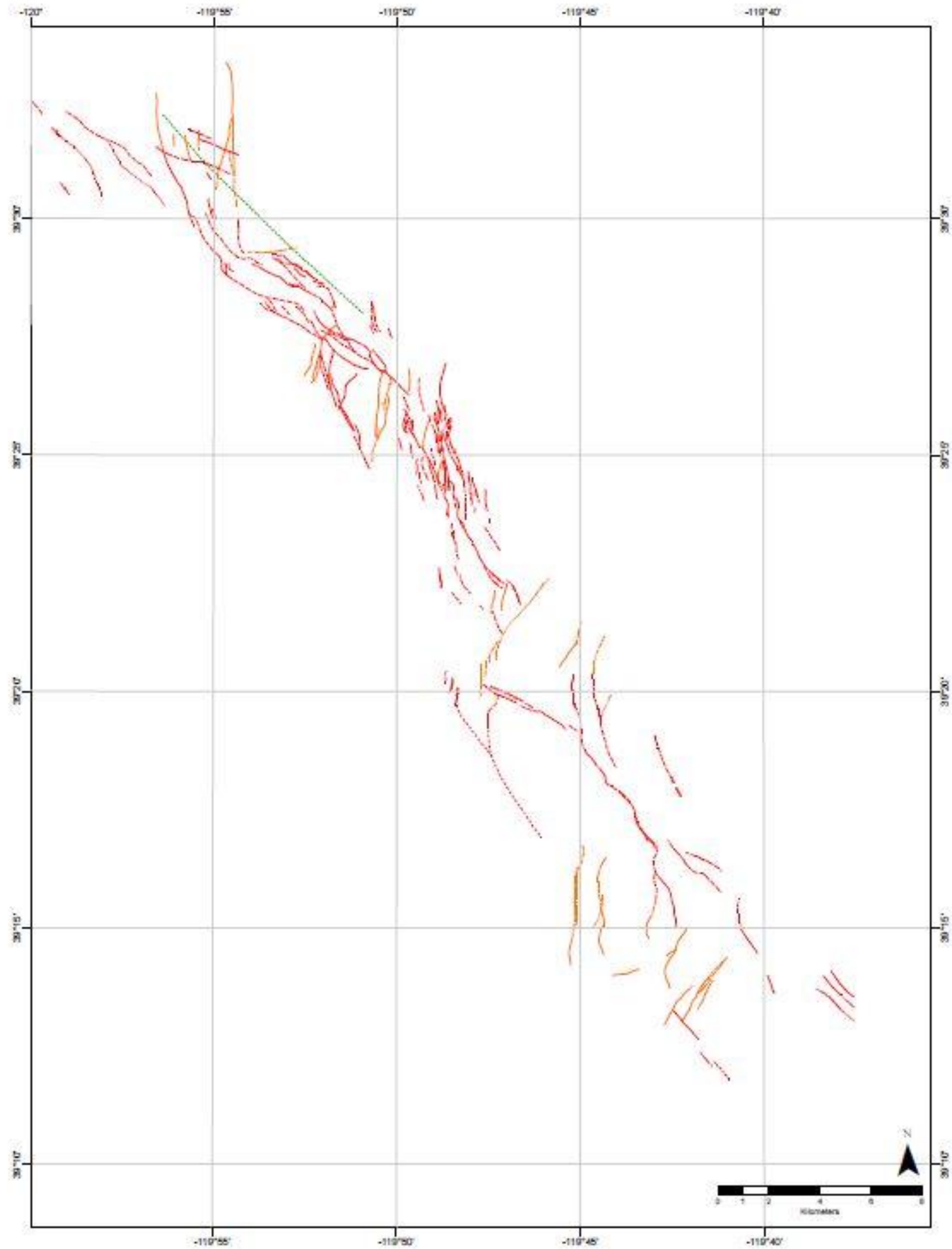


Figure 47. Fault trace map of the Washoe shear zone as developed in this study.

The history of the Washoe shear zone is not completely understood. Bell et al. (2016) suggest that strike-slip activity is incipient and is working its way into an extensional regime. Cashman et al. (2012), however, identify strike-slip faults in the Mogul area that were active in early Quaternary. Other aspects of the shear zone that may be longer lived are the Mt. Rose Pediment fault zone, which has well-developed compound alluvial fault scarps and some faults in the Northern Carson Range section that may follow older faults. Large lateral offsets along the shear zone have not been convincingly identified yet, and Henry and Perkins (2001) and Cashman et al. (2012) comment that they do not see significant lateral dismemberment of the relict Tertiary basin preserved near Verdi and Mogul. A lack of large offsets could support young activity or a low overall slip rate. The basement uplifts along the shear zone are longer lived features, so if these are dependent on the shear zone for formation, this would indicate it has been active throughout Quaternary. The notion of a developing contemporary shear zone is consistent with the discontinuous nature and distributed character of the Washoe shear zone. More detailed study of the faults within the shear zone should shed greater light on the history of the Washoe shear zone.

There are many trenching opportunities along the Washoe shear zone that will offer great insights no doubt. Some of the larger compound fault scarps in the Mt. Rose Pediment fault zone may give the most complete histories of that part of the fault; private trenching studies showed possible colluvial wedges and the largest offsets of the cemented units. Other compound scarps could similarly offer some critical paleoearthquake histories.

The importance of continuing studies of the Washoe shear zone is underscored by the consequences of an earthquake to the Reno-Carson City urban corridor. Reno would be in the near-field of ground motion and basin effects in Reno, Carson City, and beyond will likely be excited. For example, a HAZUS earthquake simulation of a magnitude 6.5 event in the Mt. Rose pediment along the shear zone estimated 20 to 90 casualties, 100 to 350 people needing hospitalization, about 5000 buildings severely damaged, and a total of over $4 billion in economic loss. This would be a catastrophic hit for the region and the state.

CONCLUSIONS

This study defines a new potential earthquake source zone near Reno, the Washoe shear zone. This zone is 28 to 48 kilometers long. The Washoe shear zone is adjacent to the Reno metropolitan area and may extend southward to east of Carson City. Most of the faults that belong to the zone have been previously mapped, the news here is linking these together as a zone and suggesting there is a through-going lateral component. The right-lateral strike-slip component is evidenced by the 2008 Mogul earthquake, en echelon stepping fault traces at multiple scales, back-facing scarps, linear troughs and drainages, apparent right deflections of some streams, and the northwest orientation within a stress regime with a west-northwest-directed least-principle horizontal stress direction.

It is fairly conclusive that the Mt. Rose Pediment fault zone and the Arrowcreek fault are late Quaternary faults and are either individual source zones or are part of larger source zones. The faults have the advantage of having Quaternary alluvial deposits over the top of them. For much of the rest of the shear zone fault traces need to be confirmed as late Pleistocene; alternative hypotheses, such as landslides, need to be refuted or adopted; and offset features, single-event offsets, and/or features that limit offset need to be discovered, mapped, measured, and documented. If Trench 1 can be confirmed to be tectonic as suspected, then the most recent event along the Caughlin Ranch fault can likely be determined by dating the faulted and unfaulted colluvium at that site.

Evaluation of the potential hazard of the Washoe shear zone is critical because of the proximity of the Reno-Carson City urban corridor.

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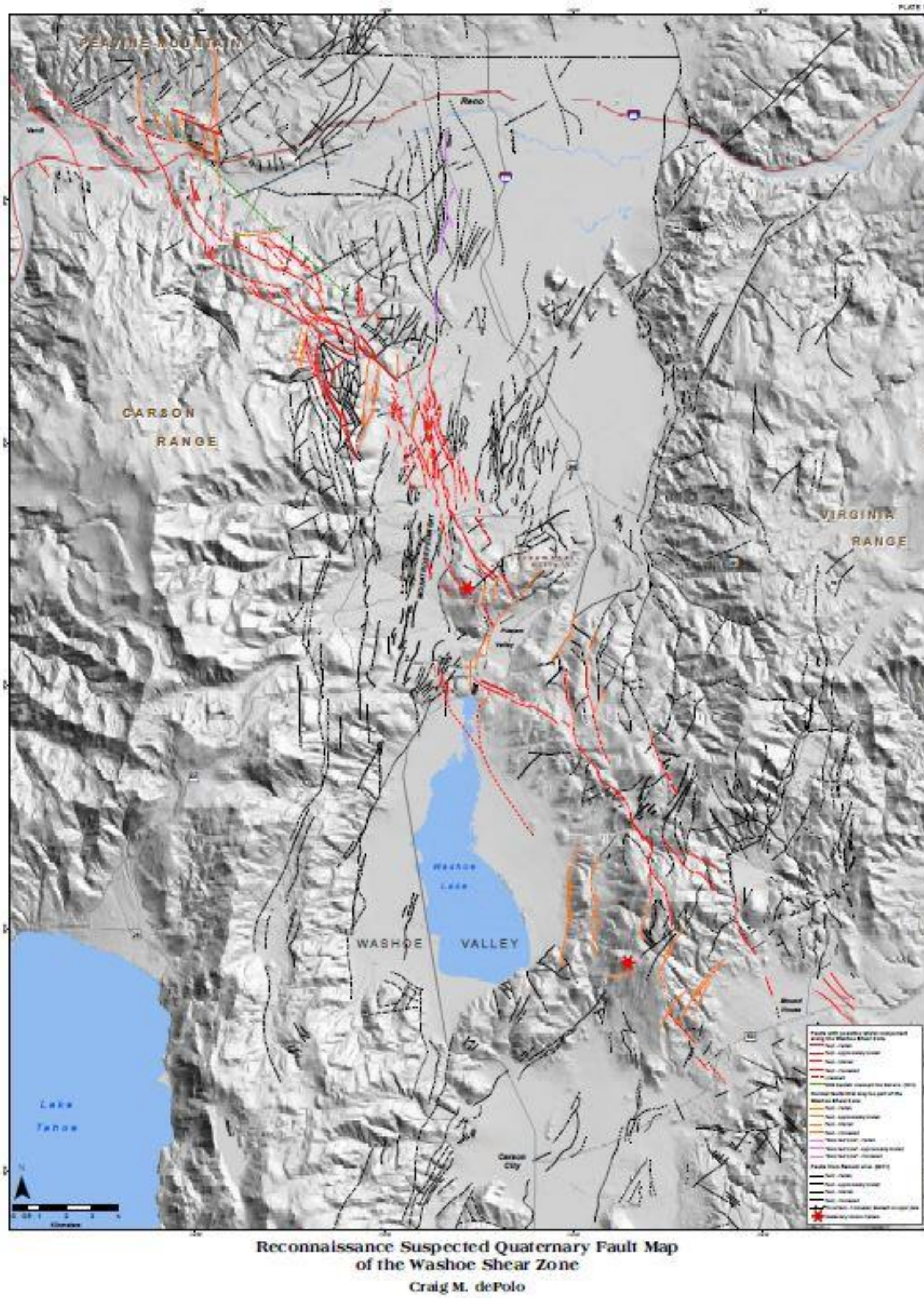
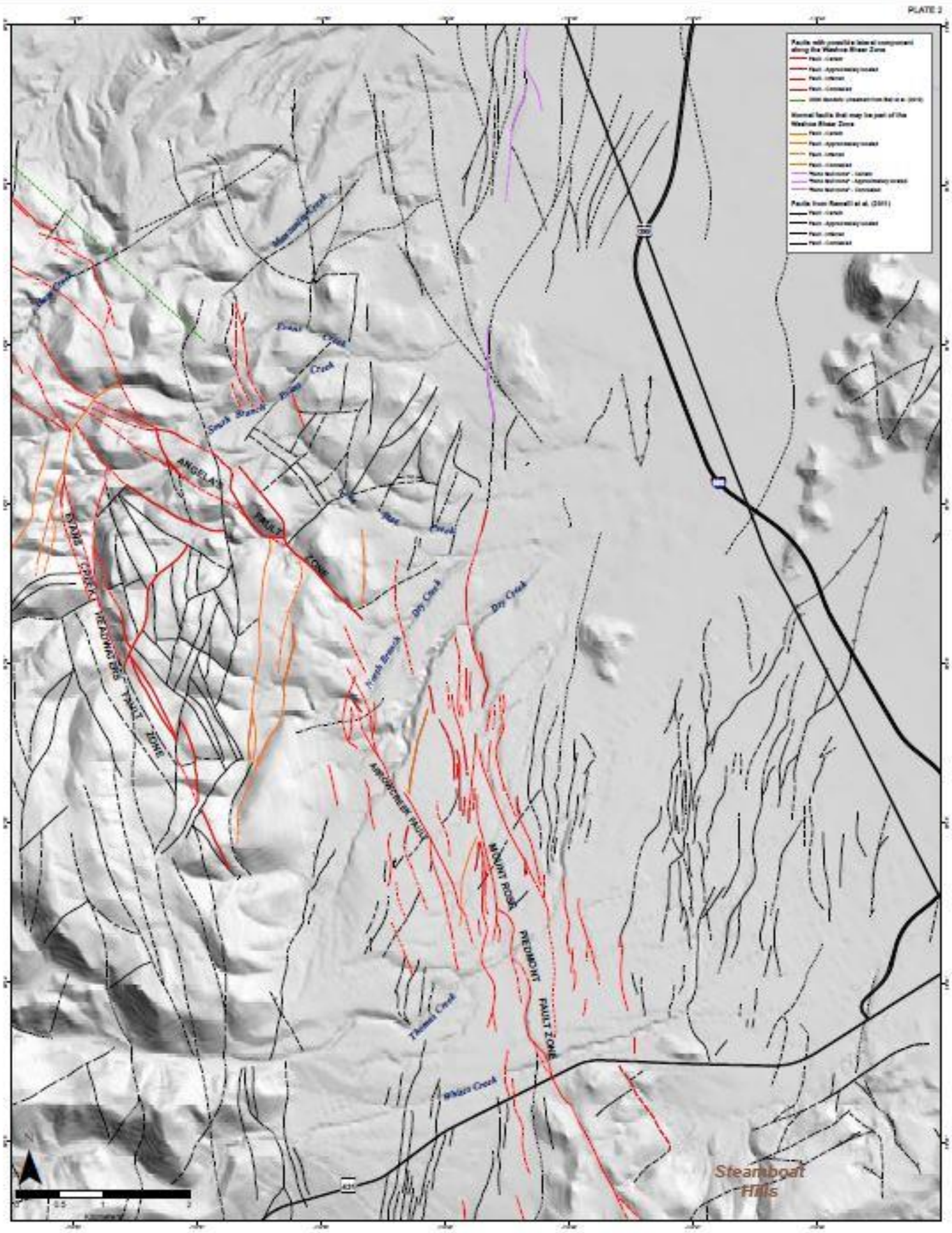


Reconnaissance Suspected Quaternary Fault Map of the Washoe Shear Zone

Craig M. dePolo

2017

Modified Fault Map of Ramelli et al. (2011) including faults mapped by Tabor and Ellen (1975), Henry and Perkins (2001), Hudson et al (2009), Trexler et al. (2012), and Cashman et al. (2012)



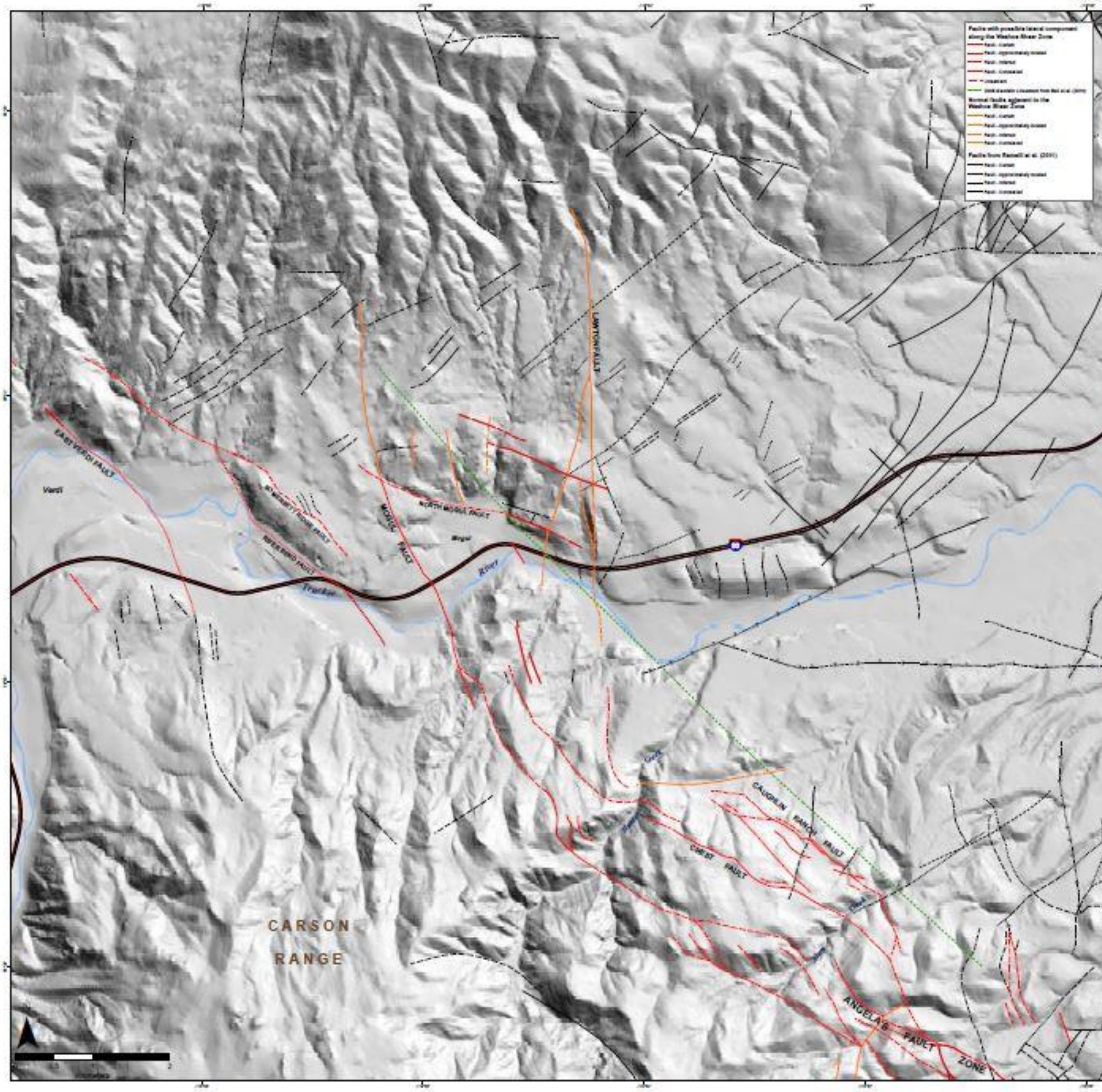
Reconnaissance Fault Map of the Mount Rose NE Quadrangle, part of the Washoe Shear Zone

Scale: 1:24,000
Projection: Universal Transverse Mercator, Zone 11 North American Datum 1983 (m)
Base map: USGS NED n40w120 1/3 arc-second 1 x1 degree ArcGrid, 2013

Craig M. dePolo
2017

Cartography and map production in ESRI ArcGIS v10.3.1 (ArcGeology v1.3) by Rachel Micander

PLATE 3



Reconnaissance Fault Map of the NW Portion of the Study Area, part of the Washoe Shear Zone

Craig M. dePolo

2017

Scale: 1:24,000
Projection: Universal Transverse Mercator, Zone 11
North American Datum 1983 (m)
Base map: USGS NED n40w120 1/3 arc-second
1 x1 degree ArcGrid, 2013

Cartography and map production in ESRI ArcGIS v10.3.1
(ArcGeology v1.3) by Rachel Micander